ALKALINE INDUSTRIAL BY-PRODUCT EFFECTS ON PLANT GROWTH IN ACIDIC-CONTAMINATED SOIL SYSTEMS

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Abstract In some regions of the United States i) the near proximity of alkaline industrial by-products to acidic-contaminated landscapes in concert with ii) low acquisition cost, make these by-products an attractive option for soil remediation projects. The objective of this research was to determine whether acidic-contaminated soil systems amended with alkaline industrial by-products enable plant growth equivalent to that attained with a commercial grade mixture of $CaCO_3$ and CaO. In addition, it was determined whether an alkaline by-product dosage threshold existed, above which plant growth was impaired.

Three types of cement kiln dust (CKD), three types of lime kiln dust (LKD), and two other alkaline by-products(Dicalcium Silicate, Carbide Lime) were evaluated in this investigation. These alkaline by-products, and the standard treatment composed of a commercial grade $CaCO_3$/CaO mixture, were applied to metalliferous tailings (pH 1.8) and metal contaminated soil (pH 5.0) and plant growth was evaluated.

Calcium carbonate equivalence of alkaline by-products ranged from modest (69 %) to high (127 %) and each contained compounds of $CaCO_3$, CaO and $Ca(OH)_2$ in amounts suitable for precipitation of metal contaminants in an acidic soil system. Most alkaline products contained enriched metal concentration including Al, As, Ba, B, Cd, Cr, Cu, Mn, Ni, Pb, Se, and Zn. Metals were often present at phytotoxic concentrations in the alkaline by-product matrix which had a pH that ranged from 9.9 to 13.7. However, evidence indicted phytotoxic concentrations may have been mitigated i) when diluted in the soil profile at a typical application rate of 2 % to 10 % (soil dry weight basis), and ii) by the amended soil pH in the range of 7.0 - 8.4 where these metal contaminants were present at low concentrations in the soil solution. Since metal contaminants are being incorporated into the root zone that may cause phytotoxic effects if the soil pH migrates outside the 7.0 - 8.4 boundary condition in the future, increased risk results when using some alkaline by-products.

All alkaline products produced a desired soil pH (7.0 - 8.4) in the root zone during plant growth tests. Following a 111 day plant growth period with Basin Wildrye and Redtop all alkaline industrial by-products tested had plant growth equal to-or greater than- the $CaCO_3$/CaO mixture. This was the case in tailings and the contaminated soil for above ground plant biomass, plant height, root biomass, root depth, and number of roots at the 5 cm and 10 cm soil depths.

For each alkaline product, including the $CaCO_3$/CaO mixture, the greater the application rate the less was plant growth. Over the alkaline product dosage range of 0 % to 12 % (soil dry weight basis) the loss in aboveground plant biomass was 65 % for Basin Wildrye and 88 % for Redtop. For this reason, it was recommended that when designing the alkaline amendment application rate for a project landscape, procedures should be used to apply the correct amount of alkaline material as opposed to an known excess.

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1.0 INTRODUCTION AND INVESTIGATION OBJECTIVES

The objective of this research was to determine whether acidic-contaminated soil systems amended with alkaline industrial by-products enable plant growth equivalent to that attained with a commercial grade mixture of $CaCO_3$ and CaO. Due to absence of a market, many types of alkaline industrial by-products have historically been landfilled in the United States. Cement kiln dust (CKD) and lime kiln dust (LKD) are two of the most common alkaline by-products, but there are many others. In some regions of the United States, I) the near proximity of these alkaline by-products to acidic-contaminated landscapes in concert with ii) low acquisition cost, make these by-products an attractive option.

Concern is present that alkaline by-products contain metals and/or soluble salts that may impair plant growth when used to treat soil acidity. Alkaline by-products frequently emanate from a combustion process and contain ash from chemical additives and the fuel such as coal, coke, and others. It has been thought that alkaline by-products with enriched concentrations of metals and/or soluble salts may provide the means for good plant growth when applied at low soil application rates, but a threshold dosage rate may exist that impairs plant growth. This investigation was conducted to better understand these concerns.

Three types of CKD, three types of LKD, and two other alkaline by-products(Dicalcium Silicate, Carbide Lime) were evaluated in this investigation. These alkaline by-products, and the standard treatment composed of a commercial grade $CaCO_3$/CaO mixture, were applied to acidic-metalliferous soil matrices and plant growth was evaluated. Specific objectives of this investigation were as follows.

- Determine the physicochemical traits of alkaline industrial by-products.

- Determine plant growth characteristics in acidic-metalliferous soil matrices amended with alkaline by-products and a $CaCO_3$/CaO mixture.

- Determine whether a alkaline by-product dosage thresholds exist, above which plant growth is impaired.

- Identify those alkaline by-products that are suitable for in-situ treatment of acid soil systems.

2.0 RELEVANT SUPPORT LITERATURE

2.1 KILN DUST PRODUCTION IN THE UNITED STATES

The U.S. EPA estimated that in 1990 the cement industry produced approximately 14 million tons (12.7 metric tons) of cement kiln dust (CKD) from 111 plants in 38 states (Figure 1, EPA, 1999). The industry disposed of approximately 3.6 million metric tons of CKD in 1995 (EPA, 1999). There are presently 110 Portland cement plants operating in the U.S. and Puerto Rico, with California, Texas, Pennsylvania and Michigan being the chief cement producing states (EPA 1999).

Lime kiln dust (LKD) is a by-product of the production of quicklime (CaO). In 1998, quicklime was produced in 32 states and Puerto Rico at 114 operations (Figure 1,U.S.G.S. 1999).

2.2 SOURCE OF KILN DUST IMPURITIES THAT MAY INFLUENCE LAND RECLAMATION

It is important to determine the impurity composition in kiln dust to insure concentrations do not exist that could impair plant growth. Plant growth factors in kiln dust such as metal content, arsenic concentration, salinity and sodicity levels will be different for each production facility as a function of several factors as discussed below and illustrated in Figure 2.

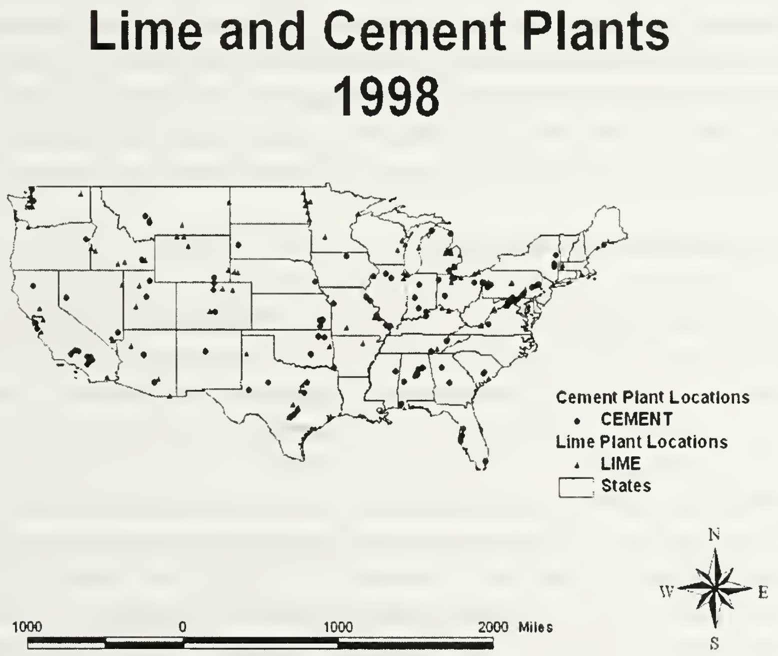

Figure 1. Location of lime and cement plants in the U.S. in 1998 (U.S.G.S. 1998).

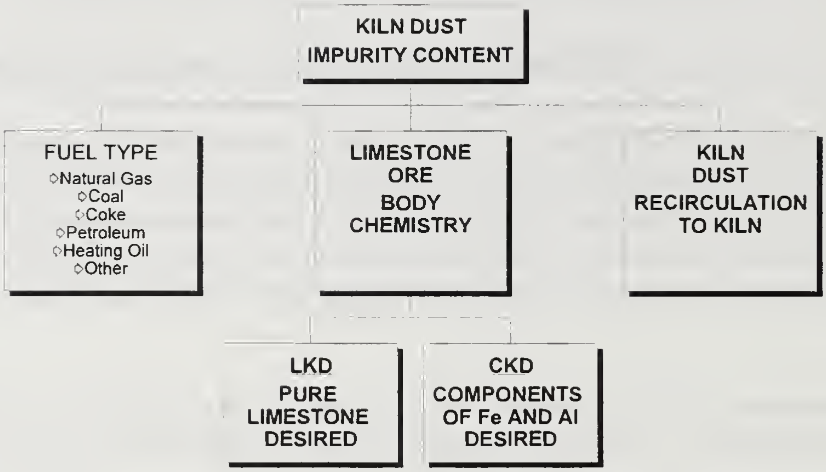

Figure 2. Some factors that influence the chemical constituents in kiln dust.

2.2.1 Kiln Fuel Effect on Kiln Dust Composition

Metals and salts in kiln dust originate from raw materials and fuels and are affected by the design and operation of the kiln. For example, the amount of lead introduced with fuels can affect the amount of lead in kiln dust. Heat energy is supplied to a kiln by burning pulverized coal, Figure 2. Chemical constituents in kiln dust are influenced by the fuel type, for example, petroleum coke, oil, natural gas, and a variety of other fuels. For all but natural gas, these fuels leave an ash that has an inherent metal content that becomes part of the kiln dust. Natural gas leaves no ash residue so this fuel does not contribute metals and salt to the kiln dust. Given the relatively low cost of coal in North America, many kilns are heated with coal.

2.2.2 Influence of the Limestone Ore Body

Companies that use kilns to produce lime (CaO) input the highest grade of limestone attainable. Therefore, ore bodies associated with this industry are typically 95 % or greater limestone. The purity of the ore body results in a low potential to introduce impurities into the LKD.

Cement production in a kiln requires a notable input of iron and aluminum oxides to facilitate product specifications. If these compounds are not present in the ore body, they must be added in specified amounts to the kiln. Therefore, ore bodies are selected to contain at least 50 % limestone and amounts of iron and aluminum (Portland Cement Association 1992). The metalliferous nature of the ore body may contain other metals, e.g. Zn, that eventually reside in the kiln ash referred to as dust. Therefore, an ore body associated with cement production may

produce kiln dust that has a greater metal-salt content compared to kiln dust emanating from lime production.

The lime science to treat acidic-metalliferous soil will generally result in kiln dust application rates of 2 to 10 % on a weight basis, i.e. 20 to 100 tons of kiln dust per 1000 tons of soil. Therefore, an enriched metal or salt concentration in kiln dust will be diluted when kiln dust is mixed into the soil system.

2.2.3 Kiln Dust Recirculation

At some kiln operations the kiln dust is returned to the kiln for continued processing. In the end, this process results in less production of kiln dust, but the resulting metal and salt levels in the final dust are more concentrated. A study by the Portland Cement Association (1992) chemically analyzed CKD at most cement manufacturing facilities in the United States. The only samples of CKD that failed to pass the Toxicity Characteristic Leaching Procedure (TCLP) test, which is used to determine whether a material is a hazardous waste, were those from kilns where the kiln dust was recirculated. These investigators concluded the single most important parameter in determining the level of trace metals in CKD is the degree of recirculation of the CKD in the kiln system.

2.3 STATE REGULATION OF INDUSTRIAL BY-PRODUCTS

Industrial by-products planned for use in agricultural lands are being regulated by government in some states. For example, in Virginia the state government developed a document titled, Guidelines for Approving Industrial Co-Products For Agricultural Use Under The Virginia Fertilizer And Agricultural Liming Materials Laws (Virginia Department of Agriculture and Consumer Services 1995). The law enables the State to require verification of industrial co-products using a 3-step investigation.

- Complete physicochemical analysis of the industrial co-product.
- Greenhouse pot studies utilizing relevant soil and plant materials.
- Outdoor plant growth field trials to confirm the effectiveness of the co-product.

Investigation work is often performed in concert with Virginia Tech. For example, a recent study completed by Virginia Tech evaluated the suitability of a waste lime product as a soil amendment (Daniels et al. 1996). These investigators found that the waste lime product produced desirable plant growth effects but a threshold existed. That is, application rates in excess of the threshold resulted in decreased plant productivity.

2.4 EFFORTS TO CHARACTERIZE KILN DUST PHYSICOCHEMICAL TRAITS

Haynes and Kramer (1982) analyzed kiln dust samples from 102 cement plants in the United States. Concentration of Al, Cl^-, F^-, SO_4^{-2}, Sr, Ti were consistently greater than 500

mg/kg. Lead concentration ranged high as 2500 mg/kg and 8000 mg/kg for Zn, while median values were 148 and 167 mg/kg, respectively. They determined CKD was not a hazardous waste as defined by RCRA.

The Portland Cement Association (1992) sampled kiln dust from 79 plants in the United States. All but two samples passed the TCLP test used to identify a hazardous waste. Total concentrations of 12 metals were determined and enrichment was greatest for Ba (mean 280 mg/kg) followed by Cr, Ni, As, and Pb.

Dollhopf (1996a, 1996b, 1997a,1997b) and Dollhopf and Juntunen (1995) analyzed both CKD and LKD from several facilities located in the northwest United States. All CKD and LKD evaluated had high calcium carbonate equivalence and contained desired compounds ($CaCO_3$, $Ca(OH)_2$, CaO) for neutralization of acidic-metalliferous mine waste. Some kiln dusts formed a notable quantity of coarse particles (> 0.25 mm diameter) due to having been weathered in outdoor storage areas, a physical trait that is not desired for neutralization of acidic soil, but most materials were fine textured. Both LKD and CKD contained enriched levels of metals compared to concentrations present in natural soils in the United States. However, Cu, Mn, Pb, Zn and other metals were very enriched in some CKD samples. In addition, sodium adsorption ratio in CKD was typically very high (20 - 60) which could exacerbate a preexisting sodic condition in a soil. The soluble salt content in LKD was low but this trait was not analyzed in CKD. These investigators found both LKD and CKD were capable of neutralizing acidic-metalliferous mine waste, but did not have the opportunity to evaluate these industrial by-products with plant growth tests.

May (1999) evaluated whether representative trace metal data in CKD could be obtained from a single grab sample. More that 20,000 samples were collected from two cement kilns. Results indicated that variation between samples was sufficiently large that multiple samples should be collected to accurately determine chemical traits of CKD.

2.5 PAST KILN DUST USE IN THE SOIL-PLANT SYSTEM

Redente and Richard (1998) conducted plant (Redtop, *Agrostis alba*) growth tests in the greenhouse in acidic waste rock from the Summitville Superfund Site amended with LKD, quicklime (CaO), and limestone ($CaCO_3$). They found limestone supported significantly greater plant shoot and root biomass compared to LKD. This result was attributed to the high pH produced in the root zone when LKD was applied compared to that attained with limestone.

Gitt and Dollhopf (1991) treated acidic coal waste with agriculture grade limestone and CKD at a field site in central Montana that was seeded to a mixture of grasses and forbs. They found both amendments neutralized the acidic nature of the coal waste, but limestone treatment resulted in significantly more (3 fold) plant production compared to treatment with CKD.

Dollhopf and McDaniel(1997) studied alkaline industrial by-products (Dicalcium Silicate and Flux Bar Residue) produced from a kiln during the manufacture of magnesium from dolomite. Bench top column test indicated these alkaline by-products effectively neutralized acidic mine wastes and precipitated metals of concern. However, when these by-products were used to treat acidic wastes, above ground plant (*Agropyron intermedium*, Intermediate wheatgrass) production attained with a mixture of agriculture grade limestone and a commercially produced calcium hydroxide was 20-fold that produced with Dicalcium Silicate, and no plant growth was attained with Flux Bar Residue. Mine waste application rates for Dicalcium Silicate and Flux Bar Residue were very high, 190.6 t/1000t and 129 t/1000t respectively.

ARCO Environmental Remediation, L.L.C (1999) reported LKD had been used on eight sites in the Upper Clark Fork River Basin in Montana where the landscape had become acidic and contaminated with metals due to historical overland flooding containing mine waste and/or fallout from smelter emissions. These authors indicated measurements had not been completed on all sites, but some locations exhibited notable plant establishment and growth following treatment with LKD.

Winking and Dollhopf (2000) amended acidic-metalliferous tailings with I) LKD at an application rate of 9.8 % (dry weight basis), ii) Dicalcium Silicate at an application rate of 9.5 %, and iii) a mixture of commercial grade limestone with calcium hydroxide at a 8.5 % application rate. All amendments successfully neutralized the acid conditions in the tailings. Above and below ground growth of *Thinopyrum intermedium* (Intermediate wheatgrass, var. Tegmar) and *Elymus trachycaulum* (Slender wheatgrass, var. Pryor) were the same for tailings amended with the commercial grade limestone/calcium oxide mixture and LKD, but Dicalcium Silicate amended tailings had significantly less plant growth.

Investigators reported loss in plant growth when soils were treated with CKD. Saravanan and Appavu (1998) measured decreased root length, shoot length and seedling vigor index for crops grown in soils treated with CKD. Investigators (Ignacimuthu and Muraleytharan 1994, Kaushik 1996) determined plants grown in a solution treated with CKD had a decreased mitotic index which was related to plant chromosome damage and it was suggested CKD acted as a mutagen to the plant system.

Numerous investigators reported deposition, i.e. dusting, of CKD onto plant leaves impaired growth of various plant species (Chitralekha and Dhakshinamoorthy 1998, Rao and Narayanan 1998, Durge and Phadnawis1994, Durge and Phadnawis 1998, Hegazy 1996, Prasad and Inamdar 1990, Uma and Ramana 1994, Uma and Ramana 1993). This result may be a function of the caustic nature of kiln dusts. It is likely that any caustic amendment (i.e. CKD, LKD, CaO or $Ca(OH)_2$) transferred by wind onto adjacent lands could cause impaired plant growth.

Gutenmann et al. (1994) found enriched levels of selenium in CKD resulted in significantly higher concentrations of this element in plant parts when the soil had been treated with CKD.

Investigators reported LKD and CKD improved plant growth when applied to soils at rates comparable to fertilizer application or in combination with sewage sludge treatments (Simpson and Stopes 1991, Christie et al. 2001, Lafond and Simard 1999, Lou and Christie 1997).

3.0 METHODS AND MATERIALS

3.1 TAILINGS, CONTAMINATED SOIL, PLANT GROWTH CENTER SOIL - BULK SAMPLE COLLECTION

A bulk composite **tailings** sample of approximately 680 liters (180 gallons) was collected from the opportunity D-2 pond site near to the south edge of ARTS Site 01. Stainless steel tools were used to place tailings into clean plastic cans. The sample was collected to a depth of 45 cm avoiding the initial 0 - 7 cm depth increment which contained some limestone. Similarly, a bulk composite **contaminated soil** sample of approximately 680 liters was collected from the east end of Stucky Ridge near Anaconda, Montana, specifically 10 m south of STR9808002, within the 0 - 10 cm depth increment. The MSU **Plant Growth Center soil** was composed of 33 % Bozeman silt-loam, 33 % sand and 33 % sphagnum peat (volume basis). This soil was sterilized with forced steam and used as an optimal potting medium to attain maximum plant growth.

3.2 ALKALINE INDUSTRIAL BY-PRODUCTS - BULK SAMPLE COLLECTION

These following nine alkaline industrial products were collected for this investigation.

- **$CaCO_3$/CaO Mixture**. Limestone ($CaCO_3$) was provided by Montana Limestone, Bridger, MT. Lime (CaO) was provided by Greymont, Inc. (formerly Continental Lime Company), Townsend, MT.

- **Greymont LKD**. This LKD was produced by Greymont, Inc. (formerly Continental Lime Company), Townsend, MT. A composite bulk sample, consisting of 10 subsamples, was collected from a stockpile of this LKD located in Anaconda, Montana, owned by ARCO Environmental Remediation, Limited. This LKD was produced in a kiln heated with a fuel mixture of 70 % coal and 30 % coke. The kiln process did not include recirculation of the LKD.

- **Tacoma LKD**. This LKD was produced by Greymont, Inc. (formerly Continental Lime Company, Tacoma, WA. The company referred to this LKD as "Econolime". Limestone is shipped to Tacoma where the kiln is located. ARCO Environmental Remediation, Limited purchased this LKD and had it transported by rail to Rocker, Montana where it was stockpiled. A composite bulk sample, consisting of 6 subsamples, was collected from this stockpile in Rocker, MT.

- **MT Limestone LKD**. This LKD was produced by Montana Limestone, Bridger, MT. The limestone pit and kiln are located in Frannie, WY. This LKD was produced in a kiln heated with a fuel mixture of coal and coke. Montana Limestone staff collected the bulk LKD sample and shipped it to Montana State University.

- **Holnam (CH_4) CKD**. This CKD was produced by Holnam, Inc., Three Forks, MT. The limestone pit and kiln are located in Trident, MT. The CKD was produced in a kiln heated with methane gas (CH_4). In addition to limestone, amounts of shale, sand, glass and iron ore were placed in the kiln to produce cement. The kiln process did not include recirculation of the CKD. A single bulk sample of CKD was collected from the storage silo.

- **Holnam (Coal, Coke) CKD**. This CKD was produced by Holnam, Inc., Three Forks, MT. The limestone pit and kiln are located in Trident, MT. The CKD was produced in a kiln heated with a mixture of 75 % coal and 25 % coke. In addition to limestone, amounts of shale, sand, glass and iron ore were placed in the kiln to produce cement. The kiln process did not include recirculation of the CKD. A single bulk sample of CKD was collected from the storage silo.

- **Ash Grove CKD**. This CKD was produced by Ash Grove Cement Company, Clancy, MT. The limestone pit and kiln are located in Montana City, MT. The CKD was produced in a kiln heated with a mixture of 70 % coal and 30 % coke. In addition to limestone, amounts of shale, silica, and slag iron were placed in the kiln to produce cement. Approximately one-third of the CKD was recirculated through the kiln. A single bulk sample of CKD was collected from the storage silo.

- **Dicalcium Silicate**. This kiln dust was produced by Northwest Alloys, Addy, Washington., where magnesium is produced from dolomitic limestone. The limestone pit and kiln are located in Addy, WA. Staff from Northwest Alloys collected a bulk sample and shipped it to Montana State University.

- **Carbide Lime**. This alkaline by-product was produced by Liquide Air, Missoula, MT. The by-product stockpile was located on Liquide Air properties in Missoula, MT. Carbide Lime is a by-product in the production of acetylene gas. Coke is combusted in the presence of calcium oxide to produce calcium carbide, which is then treated with water to yield acetylene and Carbide Lime. A composite bulk sample, consisting of 10 subsamples, was collected from a stockpile in Missoula, MT.

3.3 ANALYTICAL METHODS FOR SOIL AND ALKALINE INDUSTRIAL BY-PRODUCTS

The soil samples collected from the field (tailings and contaminated soil) were mechanically homogenized prior to analysis. Samples were placed in a rotating tractor driven cement mixer at the MSU Plant Growth Center for five minutes with the tractor set at 1200 rpm. Subsamples were then collected and dried for analysis of physicochemical parameters listed in Table 1.

Table 1. Analytical testing methods for soil and alkaline industrial by-products.

Analysis	Note	Method
Gravimetric water content[2], %		ASTM C602-90, Sections 20, 23, p. 306, modified to dry LKD 110°C in nitrogen gas environment.
pH[2], s.u.		Agron. Soc. Amer., Monograph No. 9, Methods of Soil Analysis, 1965, Method 62-1.3.2.1, p. 935.
Electrical Conductivity[2], dS/m		Agron. Soc. Amer., Monograph No. 9, Methods of Soil Analysis, 1965, Method 62-2.2.3, p. 938.
Total Metals[1]	Ag, Al, As, Ba, Be, B, Ca, Cd, Cr, Cu, Fe, Hg, K, Mg, Mn, Ni, P, Pb, Se, Sn, V, Zn	Test Methods for Evaluating Solid Waste, 1986. Method 3050 (HNO_3 and H_2O_2 digestion).
Water Soluble Metals[1]	Al, As, B, Cd, Cl, Cu, Fe, Mn, Pb, Se, SO_4, Zn,	Agron. Soc. Amer., Monograph No. 9, Methods of Soil Analysis, 1965, Method 62-1.3.2.1, p. 935
Toxicity Characteristic Leaching Procedure (8 RCRA metals)[1]	As, Ba, Cd, Cr, Pb, Hg, Se, Ag	EPA, SW 846, Method 1311
Calcium Carbonate Equivalence (CCE)[1], %		Agron. Soc. Amer., Monograph No. 9, Methods of Soil Analysis, 1965, Method 91-4.2., p. 1387.
Loss on Ignition[1], %		ASTM (1980) C25-90, Section 21
Sodium Adsorption Ratio[2]	$[Na]/(([Ca] + [Mg])/2)^{1/2}$, meq/l	Agron. Soc. Amer., Monograph No. 9, Methods of Soil Analysis, 1965, Method 62-1.3.2.1, p. 935
Acid-Base Account[1]		Modified Sobek Method (RRU *et. al.*, 1987) (Sobek et al. 1978)
Lime Requirement (SMP Buffer)[1]	Lime requirement tons/1000 tons	Method 12-3 (ASA, 1982), Part 2
Particle Size Analysis[2]	% sand, silt and clay	Modified Day, Method 15-5 (ASA, 1982), Part 1
Textural Classification[2]	USDA Textural Triangle	Soil Survey Staff (1975)
% Rock Fragments[2]	$\geq$ 2 mm diameter	ASTM (1993) D421-85
% Saturation[2]		Method 27a (U.S. Salinity Lab Staff, 1969)

[1] Energy Laboratories, [2] RRU Laboratory

In addition to the standard bench top pH glass electrode method, a stainless steel pH probe (Scientific Instruments Model IQ150) was used to measure root zone pH during the plant growth period. The probe was periodically pushed into the pot substrate to the 2.5 cm soil depth and pH measured with the calibrated instrument.

3.4 PLANT SPECIES

Plant species selected for this investigation were based on their relevance to disturbed land reclamation and tolerance to saline and acidic-metalliferous soils. Perennial grasses selected are listed in Table 2.

3.5 SOIL TREATMENTS FOR PLANT GROWTH TESTS

3.5.1 Soil Treatments For Tailings, Contaminated Soil and Plant Growth Center Soil

Nine alkaline products were applied to three difference soil types (Table 3). The i) tailings had a lime requirement of 47.43 t $CaCO_3$/1000 t, the ii) contaminated soil had a lime requirement of 7.92 t $CaCO_3$/1000 t, and the iii) Plant Growth Center soil had no lime requirement. The total lime requirement for these three soil types was calculated according to Equation 1. A control treatment served to evaluate plant growth in each soil type without

t $CaCO_3$ /1000 t soil = (% HNO_3 ext.S + % Residual S) 31.25 +
23.44 (% HCl ext. S) + SMP Lime Requirement, t $CaCO_3$/1000 t soil [Equation 1]

addition of an alkaline product. The application rate was different for each alkaline product for tailings and for the contaminated soil since physicochemical traits of each product are different. An alkaline product application rate for a soil was a function of the i) calcium carbonate equivalence, ii) particle size < 60 mesh (0.25 mm), and iii) gravimetric water content. The Plant

Table 2. Characteristics of plant species used in this investigation (Munshower, 1998).

Plant Specie	Plant Common Name	Salinity Tolerance	Acid Tolerance	Metal/Non-metal Tolerance	Seeding Depth cm
Leymus cinereus, Magnar	Basin Wildrye	good to very good	acid to alkaline	Elevated heavy metals, very tolerant of water soluble arsenic in soil	1.25
Agrostis alba, Streaker	Redtop	moderate	acid	some	1.25

Table 3. Alkaline amendment application rates for tailings, contaminated soil, and Plant Growth Center soil.

Treatment [1]	Application Rate, Tons Amendment/ 1000 Tons Soil		
	Tailings	Contaminated Soil	Plant Growth Center Soil
1) Control	0	0	0
2) $CaCO_3$/CaO	29.16 $CaCO_3$ + 11.23 CaO	4.36 $CaCO_3$ + 1.87 CaO	29.16 $CaCO_3$ + 11.23 CaO
3) Greymont LKD	75.15	12.55	75.15
4) Tacoma LKD	116.60	19.47	116.60
5) MT Limestone LKD	91.25	6.24	91.25
6) Holnam (CH_4) CKD	53.31	8.90	53.31
7) Holnam (Coal, Coke) CKD	55.15	9.21	55.15
8) Ash Grove CKD	68.70	11.47	68.70
9) Dicalcium Silicate	42.35	7.07	42.35
10) Carbide Lime	73.84	12.33	73.84

[1] Note all soil treatments included fertilizer application of 30 mg/kg (60 lb/acre) nitrogen, 8 mg/kg (16 lb/acre) phosphorous, and 100 mg/kg (200 lb/acre) potassium.

Growth Center alkaline product application rate was set the same as that required for tailings. All treatments were replicated 8 times into a randomized complete block experimental design. This constituted 480 experimental pots (8 replications x 10 soil treatments x 3 substrates x 2 plant species).

3.5.2 Soil Treatments For The Alkaline Product Dosage Sequence Plant Growth Tests

Nine alkaline products were applied to the Plant Growth Center soil at seven different application rates that ranged from 0 % (0 t alkaline amendment /1000 t) to 12 % (120 t alkaline amendment /1000 t) in 20-ton increments (Table 4). All treatments were replicated 5 times a randomized complete block experimental design. This constituted 630 experimental pots (5 replications x 9 soil treatments x 7 application rates x 2 plant species).

3.6 PLANT GROWTH CONDITIONS

Initially, all soil materials treated with alkaline products had a pH >8.5 due to the presence of CaO and $Ca(OH)_2$. In order to reduce this pH, carbonation of these oxides and hydroxides of calcium was facilitated with CO_2 gas piped through each substrate in the presence

Table 4. Alkaline amendment application rates for variable dosage rate research using the Plant Growth Center soil.

Treatment[1]	Alkaline Amendment Dosage Sequence						
	0 %	2 %	4 %	6 %	8 %	10 %	12 %
	Tons Amendment/ 1000 Tons Soil						
1) $CaCO_3/CaO$	0	20	40	60	80	100	120
2) Greymont LKD	0	20	40	60	80	100	120
3) Tacoma LKD	0	20	40	60	80	100	120
4) MT Limestone LKD	0	20	40	60	80	100	120
5) Holnam (CH_4) CKD	0	20	40	60	80	100	120
6) Holnam (Coal, Coke) CKD	0	20	40	60	80	100	120
7) Ash Grove CKD	0	20	40	60	80	100	120
8) Dicalcium Silicate	0	20	40	60	80	100	120
9) Carbide Lime	0	20	40	60	80	100	120

[1] Note all soil treatments included fertilizer application of 30 mg/kg (60 lb/acre) nitrogen, 8 mg/kg (16 lb/acre) phosphorous, and 100 mg/kg (200 lb/acre) potassium.

of applied water. The carbonation treatment process required a several month period to complete. When all substrate pH levels were below 8.5, seeding was instituted.

A seed stock viability test was performed to determine the percent live seed for Basin Wildrye and Redtop. Ten seeds of each species were placed on paper towels in a petri dish and kept moist. This procedure was replicated 4 times. Percent of the seeds that germinated was recorded. Live seed was 92.0±5.4 % for Basin Wildrye and 92.0±4.8 % for Redtop.

Fifteen seeds of the same plant species were planted in each pot. Following 14 days of post-emergence plant growth, several growth characteristics were measured and then plants were thinned to five per pot. Plants were grown with 18 hours of light per day at 21° C (69.8° F). Night temperatures were maintained at 18° C (64° F).

3.6.1 Plant Growth Procedures For Tailings, Contaminated Soil and Plant Growth Center Soil

Plant growth containers were round plastic pots with dimensions of approximately 15 cm in diameter and 15 cm deep. Plants were watered at a rate of 100 ml per day. The plant growth period was 111 days.

3.6.2 Plant Growth Procedures For The Alkaline Product Dosage Sequence Plant Growth Tests

Plant growth containers were square plastic pots with dimensions of approximately 11 cm in diameter and 10 cm deep. Plants were watered at a rate of 50 ml every other day. The plant growth period was 90 days.

3.7 PLANT GROWTH MEASUREMENTS

Nine types of plant growth measurements were made and are described in Table 5. Measurement of below ground biomass, i.e. root biomass, was facilitated with a water washing procedure that separated soil from the root.

Table 5. Plant growth measurements.

Plant Growth Measurement	**Procedure**
Time To Emergence	Number of days for seedling to emerge from date of seeding.
Germination	Given the 15 seeds/pot, the number that germinated and emerged.
14 Days After Emergence	
Survival	Number of viable seedlings of those that emerged.
Shoot Height	Distance from ground to the end of the longest leaf for each plant.
Plant Harvest [1]	
Aboveground Height	Distance from the ground to the end of the longest leaf for each plant.
Maximum Root Depth[2]	The maximum root length in each growth pot measured a maximum of the depth of pot.
Root Distribution	The number of roots at 5 cm and 10 cm soil depth.
Aboveground Biomass	The aboveground biomass of all plants measured after drying at 50° C for a minimum of 48 hours.
Belowground Biomass	The belowground biomass of all plants measured after drying at 50° C for a minimum of 48 hours.

[1] Plant growth period was i) 111 days for the test using tailings, contaminated soil and Plant Growth Center soil, and ii) 90 days for the alkaline product dosage sequence plant growth test.

[2] Maximum root depth was not measured in plant growth tests associated with the alkaline product dosage sequence investigation.

3.8 STATISTICAL ANALYSES

Plant growth measurements were statistically analyzed using Sigmastat statistical software (SPSS 1997). Statistical analyses for soil pH were performed using $[H^+]$. Normally distributed data were analyzed using a two-way ANOVA to determine if treatment means were significantly different ($p < 0.05$). If treatment means were found to be significantly different, then the means were separated using the All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method). Data that were not normally distributed were transformed and analyzed using a two-way ANOVA to determine if treatment means were significantly different ($p < 0.05$). Data that were not normally distributed and could not be normalized through transformation were analyzed using the nonparametric one-way Kruskal-Wallis ANOVA on ranks to determine whether significant differences were present
($p < 0.05$).

3.9 DATA QUALITY CONTROL

Laboratory analyses were conducted on tailings, soil, and alkaline industrial products. Statements pertaining to laboratory data accuracy, precision and completeness are presented in Appendix A.

4.0 PHYSICOCHEMICAL CHARACTERISTICS OF TAILINGS AND THE CONTAMINATED SOIL

4.1. TAILINGS CHARACTERISTICS

Tailings material was collected from the D1 Opportunity Impoundment near Anaconda, MT. No plant growth was present at the field site. It contained no coarse fragments (>2 mm diameter) and had a sandy loam particle size distribution (Table 6). Tailings were acidic (pH 1.8) and saline (electrical conductivity 9.7 ds/m) due primarily to the presence of SO_4 salts and metals in solution, and the sodium adsorption ratio (0.03) was low. Water soluble concentrations of aluminum were very enriched (976 mg/l), and associated concentrations of copper, manganese, and zinc were also enriched.

In tailings, 19.2 t $CaCO_3$/1000 tons of tailings was required to neutralize the active acidity. Potential acidity emanating from sulfide minerals (0.51 %) required 15.9 t $CaCO_3$/1000 tons of tailings to neutralize this source of acidity. It was assumed that relatively insoluble sulfate minerals were present, e.g. jarosite, that had the potential to produce acidity that required an additional 3.8 t $CaCO_3$/1000 tons of tailings. The total $CaCO_3$ requirement was 47.43 t/1000 t.

4.2 CONTAMINATED SOIL CHARACTERISTICS

The contaminated soil was collected from the east end of Stucky Ridge near Anaconda, MT. Contamination in this natural soil emanated from smelter emissions. Grass growth was not present at this field site, but Canadian thistle was present and constituted approximately a 5 % plant cover. This soil had a coarse fragment content of 23 %, i.e. particles not passing a sieve with 2 mm openings, and a sandy loam particle size distribution (Table 6). The contaminated soil was acidic (pH 5.0) but was neither saline nor sodic. Total soil concentrations of arsenic (443 mg/kg) and copper (1400 mg/kg) were very enriched while lead, manganese and zinc were enriched to a lessor degree. Water soluble concentrations of arsenic (0.36 mg/l) were low in the pH 5.0 soil matrix, while copper (22.5 mg/l) and zinc (10.5 mg/l) were the most enriched metals in the soil solution.

In order to neutralize the active acidity in this contaminated soil, 5.4 t $CaCO_3$/1000 tons of soil would be required. Potential acidity emanating from sulfide minerals was small (0.03 %) and required 0.9 t $CaCO_3$/1000 tons of soil to neutralize this source of acidity. The total $CaCO_3$ requirement was 7.92 t/1000 t.

Table 6. Physicochemical characteristics of tailings and contaminated soil.

		Lime Requirements (%)											
Sample Type	SMP Active Acidity analysis $tCaCO_3/1000t$	HCl Extractable S	HNO_3 Extractable S	Residual S	H_2O Extractable S	Total S	Neut. Pot. t/1000t as $CaCO_3$	Acid Pot. t/1000t as $CaCO_3$	Acid Base Pot. as $CaCO_3$	Non-Sulfate Sulfur	H_2O by Weight	Substrate > 2 mm	Total Lime Requirement $tCaCO_3/1000t$
Contaminated Soil	5.4	0	0.01	0.02	0.01	0.04	< 1	1	-1	0.03	1.38	23.0	7.92
Tailings	19.2	0.12	0.44	0.07	0.51	1.14	< 1	20	-20	0.63	6.01	0	47.43

				Water Saturated Paste Extract (mg/l)								
Sample Type	pH	EC ds/m	Sodium Adsorption Ratio	Ca meq/l	Mg meq/l	Na meq/l	Al	As	Cu	Pb	Mn	Zn
Contaminated Soil	5.0	0.60	0.32	2.84	0.36	0.42	1	0.36	22.5	< 1	4.6	10.5
Tailings	1.8	9.7	0.03	27.6	23.3	0.14	976	6.8	99.0	< .01	183	81.4

	Total Concentration (mg/kg)					
Sample Type	Al	As	Cu	Pb	Mn	Zn
Contaminated Soil	11400	443	1400	138	241	311
Tailings	2680	76	162	273	93	94

	% Passing Dry Sieve Size				Particle Size Analysis				
Sample Type	10 mesh 2.0 mm	60 mesh 0.25 mm	Calcium Carbonate Equivalence	Loss on Ignition	% Sand	% Silt	% Clay	Textural Class	Saturation Percentage %
Contaminated Soil	77	ND*	0.1	ND	73.4	16.6	10	sandy loam (sl)	24.1
Tailings	100	ND	0.1	ND	58.4	30	11.6	sandy loam (sl)	36.0

*ND = Not Determined.

5.0 PHYSICOCHEMICAL TRAITS OF ALKALINE INDUSTRIAL BY-PRODUCTS AND COMMERCIAL LIME AND CALCIUM CARBONATE

5.1 PARTICLE SIZE DISTRIBUTION

That portion of an alkaline amendment passing a 60 mesh sieve (0.25 mm) is chemically reactive for neutralization of soil acidity. This is true for $CaCO_3$. However, both CaO and $Ca(OH)_2$ are each approximately 100 times more soluble in water compared to $CaCO_3$. Thus the coarse particles (>60 mesh) of an alkaline amendment that pass a 60 mesh sieve following a 16 hour period of shaking in a beaker of water are considered reactive CaO and $Ca(OH)_2$.

All alkaline amendments passed the 60 mesh screen except for Greymont Lime Kiln Dust (LKD), Tacoma LKD, and Carbide Lime (Table 7). Following dry and wet sieving procedures, 19.2 % of the Greymont LKD failed to pass the 60 mesh sieve, while 55.1 % of the Tacoma LKD failed and 33.5 % of the Carbide Lime failed. Portions of an alkaline amendment failing to pass a 60 mesh sieve are considered inert, and must be accounted for during calculation of an application rate to neutralize an acidic soil system.

5.2 ALKALINE INDUSTRIAL BY-PRODUCT WATER CONTENT

Gravimetric water content of alkaline by-products ranged from 0.0 – 34.3 % (Table 7). By-products stored in silos typically had a very low water content, while those stockpiled outdoors and not covered had higher water contents.

5.3 ALKALINE INDUSTRIAL BY-PRODUCT CHEMISTRY

5.3.1 By-product Composition - Loss on Ignition and Calcium Carbonate Equivalence

The loss on ignition (LOI) laboratory test is used to determine the $CaCO_3$ content of a alkaline amendment. If a material is pure $CaCO_3$, it will lose 44 % of its mass after ignition in accordance with Reaction [1]. If the alkaline amendment loses less than 44 % of its mass after

$$CaCO_3 + \text{Heat} \rightarrow CaO + CO_2\uparrow \qquad \text{[Reaction 1]}$$

ignition, then proportionately less $CaCO_3$ is present. The interpretation of the LOI test can be complicated by the presence of $Ca(OH)_2$. If $Ca(OH)_2$ is present, the LOI test will remove its molecular bound water in accordance with Reaction 2. Therefore this loss in mass as water

$$Ca(OH)_2 + \text{Heat} \rightarrow CaO + H_2O \qquad \text{[Reaction 2]}$$

Table 7. Physicochemical characteristics of alkaline industrial by-products and commercial grade lime.

Sample Type	% Passing Dry Sieve Size		% Passing Wet Sieve 60 mesh 0.25 mm	% 60 mesh minus material Wet + Dry	Calcium Carbonate Equivalence %	Loss on Ignition %	Toxicity Characteristic Leaching Procedure (TCLP) mg/l							
	10 mesh 2.0 mm	60 mesh 0.25 mm					As	Ba	Cd	Cr	Pb	Hg	Se	Ag
Greymont LKD	ND*	68.7	38.5	80.75	78.4	26.3	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
Tacoma LKD	ND	15.3	35.0	44.90	90.6	37.2	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
MT Limestone LKD	ND	100	ND	100	127	9.33	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
Holnam (CH_4) CKD	ND	100	ND	100	89	26.3	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
Holnam (Coal/Coke) CKD	ND	100	ND	100	89	21.7	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
Ash Grove CKD	ND	100	ND	100	69.1	23.3	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
Dicalcium Silicate	ND	100	ND	100	112	0.99	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
Carbide Lime	ND	30.2	52.0	66.49	96.6	38.3	< 0.5	< 10	< 0.1	< 0.5	< 0.5	< 0.02	< 0.1	< 0.5
$CaCO_3$	ND	100	ND	100	97.6	ND	ND	ND	ND	ND	ND	ND	ND	ND
CaO	ND	19.0	100	100	169	ND	ND	ND	ND	ND	ND	ND	ND	ND
TCLP Regulatory Limit							5	100	1	5	5	0.2	1	5

* ND = Not Determined

Continued ➜

Table 7. Physicochemical characteristics of alkaline industrial by-products and commercial grade lime - Continued.

Sample Type	pH s.u.	EC ds/m	Sodium Adsorption Ratio	H_2O by Weight %	Water Saturated Paste Extract (mg/l)														
					Ca meq/l	Mg meq/l	Na meq/l	Al	As	B	Cd	Cu	Fe	Pb	Mn	Se	Zn	SO_4	Cl
Greymont LKD	9.6	2.2	0.41	0.32	69.8	< 0.01	2.47	< 1	< 0.01	< 1	< 0.01	< 0.01	< 0.1	< 0.01	< 0.01	0.05	< 0.1	1380	160
Tacoma LKD	10.1	0.91	1.8	15.5†	28.4	< 0.01	6.8	< 1	< 0.01	< 1	< 0.01	< 0.01	< 0.1	< 0.01	< 0.01	< 0.01	< 0.1	7	22
MT Limestone LKD	10.[illegible]	1.2	0.26	0	81.3	< 0.01	[illegible].69	< 1	< 0.01	< 1	< 0.01	< 0.01	< 0.1	< 0.01	< 0.01	0.0[illegible]	< 0.1	1680	279
Holnam (CH_4) CKD	13.7	97.3	40.1	0.03	3.35	< 0.01	51.9	< 2	0.55	5	< 0.01	< 0.02	0.4	0.7	< 0.02	3.31	1.3	15300	1070
Holnam (Coal/Coke) CKD	13.7	66.8	41.8	0	12.1	< 0.01	103	< 2	0.03	< 2	< 0.01	< 1	< 1	0.02	< 1	0.1	< 1	28100	1050
Ash Grove CKD	13.5	79.2	28.5	< 1	[illegible].09	< 0.01	49.9	< 1	0.36	< 1	< 0.1	0.[illegible]	< 0.1	0.2	< 0.01	1.3	1.9	48100	1180
Dicalcium Silicate	1[illegible].7	[illegible].2	0.04	0	20	< 0.01	0.14	464	< 0.01	< 1	< 0.01	0.20	< 0.1	< 0.01	< 0.01	0.01	< 0.1	< 1	3
Carbide Lime	11.9	1.64	0.02	34.3†	41.9	< 0.01	0.09	< 1	< 0.01	< 1	< 0.01	< 0.1	< 0.1	< 0.01	< 0.01	0.01	< 0.1	5	87
$CaCO_3$	8.0	0.56	0.38	0	[illegible]	0.5[illegible]	0.[illegible]	< 1	< 0.01	< 1	< 0.01	< 0.1	0.2	< 0.01	< 0.01	< 0.01	< 0.1	59	43
CaO	12.3	4.9	0.11	0	50.9	< 0.01	0.57	< 1	< 0.01	< 1	< 0.01	< 0.1	< 0.1	< 0.01	< 0.01	< 0.01	< 0.1	134	6

† - Amendment dried prior to analytical procedures, moisture content applicable in the field.

Continued →

Table 7. Physicochemical characteristics of alkaline industrial by-products and commercial grade lime - Continued.

Sample Type	Total Concentration (mg/kg)																					
	Al	As	Ba	Be	B	Cd	Ca	Cr	Cu	Fe	Pb	Mg	Mn	Hg	Ni	K	Se	Ag	Sn	P	V	Zn
Greymont LKD	16300	5	475	< 5	137	4	309000	< 5	18	4290	107	9700	325	< 1	129	368	5	< 5	< 5	228	454	49
Tacoma LKD	2810	11	23	< 5	7	< 1	281000	< 5	20	4210	18	2790	18	< 1	7	191	< 5	< 5	< 5	179	18	49
MT Limestone LKD	16300	< 5	862	< 5	137	1	416000	42	13	5310	5	13800	228	< 1	< 5	1720	< 5	< 5	< 5	117	18	23
Holnam (CH_4) CKD	12000	13	77	< 5	18	4	295000	59	18	10700	205	7350	228	< 1	< 5	40600	< 5	< 5	< 5	131	25	219
Holnam (Coal/Coke) CKD	11200	9	161	< 5	94	2	294000	83	10	10100	94	7920	276	< 1	< 5	25100	< 5	< 5	< 5	219	94	115
Ash Grove CKD	9380	15	131	< 5	20	5	237000	33	45	7270	117	9230	247	< 1	43	73200	5	< 5	< 5	117	43	467
Dicalcium Silicate	67100	< 5	24	< 5	< 5	< 1	345000	< 5	< 5	335	< 5	29100	7	< 1	< 5	39	< 5	< 5	< 5	94	< 5	< 5
Carbide Lime	3070	< 5	11	< 5	6	< 1	272000	< 5	< 5	42	< 5	179	< 5	< 1	< 5	< 50	< 5	< 5	< 5	18	6	< 5
$CaCO_3$	794	< 5	17	< 5	< 5	< 1	347000	< 5	< 5	1140	< 5	1140	85	< 1	< 5	368	< 5	< 5	< 5	94	7	10
CaO	1100	< 5	26	< 5	< 5	< 1	556000	78	6	856	< 5	9590	159	< 1	< 5	129	< 5	< 5	< 5	101	6	18

could mistakenly be interpreted as CO_2 loss [Reaction 1], which would cause an overestimation of $CaCO_3$ content. Given the mass of $Ca(OH)_2$, it has the potential to lose 24 % of its weight during LOI. In the laboratory, ignition of these by-products was performed in a furnace with an air atmosphere. In addition to error associated with water loss from $Ca(OH)_2$ during ignition, the air atmosphere in the furnace may cause analytical error. The CO_2 in air may contribute to carbonation of CaO instead of CO_2 release from $CaCO_3$ [Reaction 1], causing an overestimation of $CaCO_3$ content and associated underestimation of CaO and $Ca(OH)_2$ contents. Only one or two industry laboratories in the United States can perform this furnace test in a nitrogen atmosphere to improve analytical accuracy. Therefore, compositional values presented in Table 8 should only be viewed as qualitative approximations.

The calcium carbonate equivalence (CCE) of an alkaline by-product is a measure of its acid neutralization capability compared to pure $CaCO_3$. The CCE of these alkaline by-products ranged from 69.1 – 127 % (Table 8). The loss on ignition test results ranged from 0.99 to 38.3 % (Table 7) which by calculation means the $CaCO_3$ content of these by-products ranged from 2.2 to 87.0 % (Table 8). It was estimated that the CaO and $Ca(OH)_2$ content of these alkaline by-products ranged from 3.4 – 80.7 %. Compositional values in Table 8 are only estimates and may contain error.

Data presented in Table 8 indicate each alkaline industrial by-product contained the compounds $CaCO_3$, $Ca(OH)_2$ and CaO which are important for treatment of acidic-metalliferous soil substrates. Additional neutralizing compounds may be present, such as MgO, but are assumed to be in very small concentrations. It is important that the hydroxide (OH^-) and oxide

Table 8. Estimated composition of alkaline industrial by-products.

Alkaline By-Product	$CaCO_3$ Equivalence %	$CaCO_3$ Content %	CaO and $Ca(OH)_2$ Content[1] %	Other Material Content %
Greymont LKD	78.4	59.8	10.4 – 13.7	26.5 – 29.8
Tacoma LKD	90.6	84.5	3.4 – 4.5	11.0 – 12.1
MT Limestone LKD	127	21.2	59.1 – 77.8	0.9 – 19.7
Holnam (CH_4) CKD	89.0	59.8	16.3 – 21.5	18.7 – 23.9
Holnam (Coal/Coke) CKD	86.0	49.3	20.5 – 27.0	23.7 – 30.2
Ash Grove CKD	69.1	53.0	9.0 – 11.8	35.2 – 38.0
Dicalcium Silicate	112	2.2	61.3 – 80.7	17.1 – 36.5
Carbide Lime	96.6	87.0	5.4 – 7.1	5.9 – 7.6

[1] Range based on the assumption that either I) CaO is present (not $Ca(OH)_2$) with a CCE of 179 %, or ii) $Ca(OH)_2$ is present (not CaO) with a CCE of 136 %.

(O) compounds of calcium be present to raise the amended soil pH up into the 10 – 12 range such that metal contaminates can effectively precipitate out of the soil solution, and consequently not be available for plant uptake. Both $Ca(OH)_2$ and CaO in alkaline by-products must undergo carbonation [Reactions 3 - 7] to form $CaCO_3$ in the soil system to facilitate a suitable soil pH for plant growth. A soil system containing $CaCO_3$, as opposed to $Ca(OH)_2$ and/or CaO, will have a soil pH less than 8.4.

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad \text{[Reaction 3]}$$

$$Ca(OH)_2 \rightarrow Ca^{++} + 2OH^- \qquad \text{[Reaction 4]}$$

$$OH^- + CO_2 \rightarrow HCO_3 \qquad \text{[Reaction 5]}$$

$$HCO_3^- + OH \rightarrow CO_3^= + H_2O \qquad \text{[Reaction 6]}$$

$$CO_3^= + Ca^{++} \rightarrow CaCO_3 \qquad \text{[Reaction 7]}$$

5.3.2 Alkaline Industrial By-product Soluble Salt Content - Salinity and Sodicity

The soluble salt content of an alkaline by-product refers to the inorganic constituents that are appreciably soluble in water. In general, the growth of salt sensitive plant species may be impaired when the soil electrical conductivity is > 4 ds/m. Soil dispersion and associated loss of structure and decreased water permeability rate may occur when the sodium adsorption ratio† is > 10 for fine textured soils and > 20 for coarse textured soils.

Cement kiln dust (CKD) samples were both saline (66.8 – 97.3 ds/m) and sodic (SAR 28.5 – 40.1) (Table 7). Conversely, **lime** kiln dust (LKD) samples, Dicalcium Silicate and Carbide Lime were neither saline (0.2 – 2.2 ds/m) nor sodic (0.02 – 1.8). CKD salinity may emanate from high concentrations of water soluble SO_4^{-2} (15300 – 48100 mg/l) and Cl^- (1070 – 1180 mg/l) in association with the cations Ca^{+2}, Mg^{+2}, Na^+ and K^+. These sulfate and chloride salts were either added during the manufacturing of cement or were a component of the fuel ash remaining in the kiln. CKD salinity is sufficiently high that an amended soil may be elevated into a range that could impair plant growth of salt sensitive species. Assuming the CKD field application rate will range from 2 – 10 % of the soil mass, the soil salinity could be increased 1.3 – 9.7 ds/m. Given these same assumptions, the soil sodium adsorption ratio (SAR) could be increased 0.4 – 4.0 units. Most acidic soils are not sodic, so an increase of 0.4 – 4.0 SAR units when CKD is applied may not notably impair either the soil physical condition or plant growth. However, the potential increase in soil salinity from CKD may be sufficient to impair plant growth during periods when water availability is not abundant.

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† Sodium Adsorption Ratio = $[Na]/(([Ca]+[Mg])/2)^{1/2}$, meq/l.

In plant growth tests discussed later in this document, alkaline amendments were mixed into Plant Growth Center potting soil at application rates that ranged from 0 % to 12 % (dry weight basis). Following a 90 day plant growth period the soil electrical conductivity was measured in one replication of the experiment (Table 9). All alkaline products increased soil salinity across the application rate range of 0 - 12 %. Soil salinity increases associated with the amendments $CaCO_3/CaO$, Dicalcium Silicate and Carbide Lime ranged from 0.32 - 1.87 ds/m, while increases for LKD ranged from 0.07 - 3.09 ds/m, and increases for CKD ranged from 0.49 - 15.95 ds/m. Soil treatment with CKD resulted in a saline soil, defined as having an electrical conductivity > 4 ds/m, for application rates low as 4 % (40 tons CKD/1000 tons soil). Under conditions of abundant plant available water, these measured increases in soil salinity with alkaline amendment use will likely not impair plant growth. However, under conditions of plant water stress, these increases in soil salinity may impair plant growth due to the osmotic potential created between salt and water within the soil matrix. The plant has to expend greater energy to uptake water from the salt enriched soil matrix compared to a soil system not enriched in salt, which can cause a loss in plant growth.

Table 9. Electrical conductivity of Plant Growth Center potting soil as a function of alkaline amendment application rate.

Amendment	**Soil Electrical Conductivity, ds/m**						
	Alkaline Amendment Application Rate (dry weight basis)						
	0 %	**2 %**	**4 %**	**6 %**	**8 %**	**10 %**	**12 %**
Greymont LKD	0.94[1]	2.01	2.22	2.70	2.46	3.02	3.35
Tacoma LKD	0.87	0.94	1.55	2.03	1.20	1.32	1.70
MT Limestone LKD	0.65	2.38	2.75	2.78	3.74	2.72	3.00
Holnam (CH_4) CKD	0.89	1.38	1.87	2.68	4.45	5.82	7.08
Holnam (Coal, Coke) CKD	0.75	1.64	2.30	3.17	3.36	4.10	5.54
Ash Grove CKD	0.68	3.23	5.09	8.13	10.66	12.94	16.63
Dicalcium Silicate	0.54	1.24	1.02	1.39	0.86	1.35	0.98
Carbide Lime	0.76	1.71	1.53	2.22	1.30	2.63	1.10
$CaCO_3/CaO$	0.74	1.26	1.46	1.05	2.00	1.32	1.35

[1] n = 1. Plant Growth Center potting soil was analyzed in replication number five.

5.3.3 Alkaline Industrial By-product pH

The pH of all alkaline by-products ranged from 9.6 to 13.7 (Table 7). These high values emanate from the presence of $Ca(OH)_2$ and/or CaO in combination with $CaCO_3$ in each alkaline by-product.

5.3.4 Alkaline Industrial By-product TCLP Test

All alkaline by-products were subjected to the Toxicity Characteristic Leaching Procedure (TCLP) to ascertain whether any one could be considered a hazardous waste material. All by-products passed the TCLP test and are not considered a hazardous waste material (Table 7).

5.3.5 Alkaline Industrial By-product Chemical Enrichment

As discussed below, alkaline industrial by-products often contained metal contaminants at concentrations phytotoxic to plant growth (Table 7). However, phytotoxic concentrations may be mitigated when I) applied to soils at an application rate of 2-10 % of the soil mass which facilitates dilution of the amendment metal chemistry, and ii) the change in amendment pH from a range of 9.6 - 13.7 to the soil pH of 7.0 - 8.4 results in decreased contaminant solubility in the soil solution.

The water soluble metal content of an alkaline by-product at its pH, which ranged from 9.6 to 13.7, may be significantly different compared to an amended soil where the final pH will be in a target range of 7.0 - 8.4. Consequently efforts were made to understand the solubility of metals in the soil solution across the entire pH range of 7.0 to 13.7. It was predicted that water soluble metal concentration in alkaline by-products would be at lower concentration in an amended soil (pH 7.0 - 8.4) compared to its water soluble metal concentration at pH 9.6 - 13.7. As will be discussed below, certain water soluble metal concentrations of alkaline industrial by-products were clearly phytotoxic, however, no toxicity appeared to be in the amended soil system having a pH of 7.0 - 8.4.

Alkaline industrial by-products will be applied to acidic-contaminated soil systems at various application rates ranging up to 10 %, i.e. 100 tons amendment/1000 tons soil. Often a by-product contained a total metal concentration that was phytotoxic. However, calculation indicates amendment incorporation into the soil profile results in notable dilution that decreases the risk of a phytotoxic response.

In summary, measurement of alkaline by-product metal content revealed contaminant concentrations that would produce phytotoxic symptoms in plants. However, by-product dilution during soil incorporation and a decrease in metal solubility following treatment implementation generally led to interpretations that these alkaline products would not produce phytotoxic symptoms in the plant root zone. Uncertainty associated with these interpretations is present,

thus plant growth tests presented later in this report provide additional information regarding by-product phytotoxicity.

5.3.5.1 Vanadium

Total vanadium (V) was enriched 2-8 times in LKD and CKD compared to control materials (Table 7). Control alkaline products were $CaCO_3$ (limestone) and CaO (quicklime). One notable exception was Greymont LKD which was enriched 65 times (454 mg/kg) greater than the control (7 mg/kg). Kabata-Pendias and Pendias (1984) reported surface soils in the United States contain 7 - 300 mg/kg V and sedimentary rocks such as limestone typically contain 10-45 mg/kg V. Gough et al. (1979) reviewed the topic of V phytotoxicity and stated that there are no reports indicating V toxicity under field conditions. However, he stated under experimental conditions, V concentrations as high as 0.5 ppm in the nutrient solution, and 140 ppm in the soil solution, may be toxic to plants. Kaplan et al. (1989) reported dosages of 3 and 6 mg/l V were applied in a hydroponics study that induced visual toxicity symptoms in beans that increased with V concentration. He stated part of the toxicity effect of V on plants was related to the depression of calcium and possibly manganese uptake by the plant which leads to nutrient deficiency. In 1990, Kaplan et al. reported on a study where both sand and loamy sand soils were prepared with 1, 20, 40, 60, 80, and 100 mg/kg total V. At the two highest concentration of V, the sand soil had significantly less plant biomass of *Brassica oleracea*, but the loamy sand soil showed no effect on plant growth. These investigators also evaluated seed germination as a function of V in soil solutions that ranged from 0-75 mg/l. Low concentrations of V (1 mg/l) stimulated radicle elongation while slightly greater concentration (3 mg/l) caused severe toxicity. These investigations suggest high concentrations of V in soil systems have potential to impair plant growth. The concentration of V that will cause impaired plant growth is dependent upon the plant species present and the soil physicochemical characteristics.

Greymont LKD was produced from a kiln fuel mixture of 70 % coal and 30 % coke. Ash from these fuels likely caused the highly enriched concentrations of V found in the CKD. Following the 90 day plant growth period, pots amended with Greymont LKD were composited and a subsample analyzed for total V in the soil matrix and in the extract from a water saturated paste extract (Table 10). At the Greymont LKD application rates used in this research (12.55 - 75.15 tons/1000 tons), neither the total nor the water extractable concentrations were at levels that would impair plant growth. It is likely that the V content of this LKD will vary over time as a function of fuel chemistry in the kiln, combustion efficiency and other processing variables. Total V should be periodically measured in LKD to ensure the concentration is not greatly exceeding 454 mg/kg total V measured in this research.

5.3.5.2 Aluminum

Total aluminum (Al) was enriched 2-30 times in alkaline industrial by-products compared to the control(limestone and quicklime). Dicalcium Silicate contained the greatest concentration of total Al (67,100 mg/kg) (Table 7). The associated water saturated paste extract for Dicalcium

Table 10. Total and water soluble concentrations of vanadium (V) following a 90 day plant growth period in tailings, contaminated soil, and Plant Growth Center soil amended with Greymont LKD.

Sample Type	Greymont LKD Application Rate tons/1000 tons	Vanadium	
		Total Concentration mg/kg	Water Saturated Paste Extract mg/l
Tailings	75.15	41	<0.5
Contaminated Soil	12.55	37	<0.5
Plant Growth Center Soil	75.15	66	<0.5

Silicate contained 464 mg/l Al, while all other alkaline industrial by-products contained < 2 mg/l. Natural soil solutions contain approximately 0.4 mg/l Al (Kabata-Pendias and Pendias (1984), and Munshower (1994) reported water extractable concentrations of 1 - 5 mg/kg may be phytotoxic. When Dicalcium Silicate is used as a soil amendment all water soluble aluminum in Dicalcium Silicate (464 mg/l) must transform into a solid phase precipitate that is unavailable for plant uptake. If a portion of the by-product Al remains in solution in the plant root zone, phytotoxic conditions would likely be present.

The solubility diagram (Figure 3) shows both Al^{3+} and $Al(OH)^{2+}$ are present in high concentration when the pH is < 5.5, and $Al(OH)_4^-$ is present in high concentration when the pH is > 8.5. Dicalcium Silicate contained 464 mg/l water extractable Al at a pH of 10.4 (Table 7). The 464 mg/l equates to 1.7×10^{-1} moles/l which is plotted on Figure 3 as a dot located above pH 10.4. Therefore, in an amended soil having a pH of 7.5, for example, the Al concentration in the soil solution is predicted to be 3.0×10^{-4} moles/l in Figure 3, which equates to 0.80 mg/l Al. An amended soil having 0.80 mg/l Al in the soil solution is not expected to impair plant growth. Following the 111 day plant growth period discussed later in this report, the 8 replicated pots amended with Dicalcium Silicate were composited for tailings, contaminated soil, and Plant Growth Center soil, and the extract from a water saturated soil paste was analyzed for Al (Table 11). Following the carbonation process (Reactions 3 - 7) that produced a soil pH in the range of 7.0 - 8.3 and 111 day plant growth period, as predicted by the solubility diagram in Figure 3 the amount of Al in the soil solution was relatively low, ranging from < 0.5 - 2.0 mg/l. As will be discussed below, plant growth in these pots was good and was not impaired by an Al phytotoxicity issue.

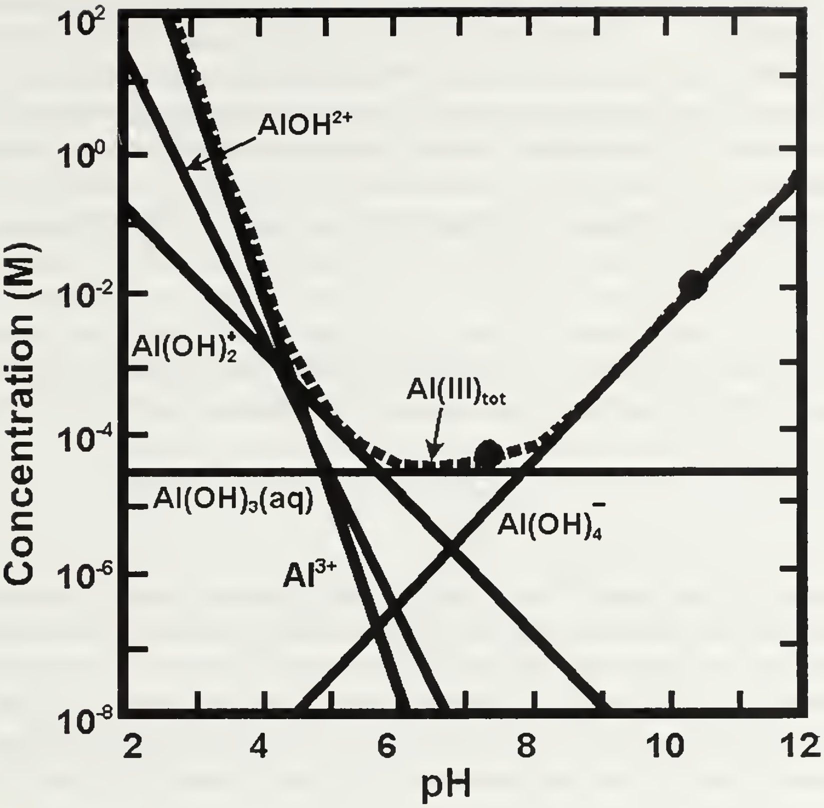


Figure 3. Aluminum concentration and chemical form present in the soil solution as a function of pH (from Stumm and Morgan 1996, concentration scale adjusted to known Al^{3+} concentration for Dicalcium Silicate at pH 10.4). Aluminum concentration in Dicalcium Silicate is shown as the dot (●) above pH 10.4, and the predicted aluminum concentration in an amended soil is shown as a dot above pH 7.5.

Table 11. Water soluble concentrations of aluminum (Al) in tailings, contaminated soil, and Plant Growth Center soil amended with Dicalcium Silicate.

Sample Type	Dicalcium Silicate Application Rate, tons/1000 tons	Water Saturated Paste Extract, Al (mg/l)
Tailings	42.35	<0.5
Contaminated Soil	7.07	1.3
Plant Growth Center Soil	42.35	2.0

Dicalcium Silicate will infuse a large quantity of Al into the soil solution when applied as an amendment. During the 4 - 12 month period following application the soil pH will be > 8.5, i.e. during the "pH mellowing" or carbonation period, and the soil is expected to contain soluble Al at concentrations that are phytotoxic during this period. However, once the soil completes carbonation Reactions 3 - 7 (presented above), the soil pH should be < 8.5 and the quantity of Al in the soil solution should approach a low concentration that is not expected to impair plant growth. However, as shown in Figure 3, if the soil pH declines over time to below approximately 6.0 the Al will become soluble and could impair plant growth. Similarly, if the amended soil fails to carbonate over a period of months and the pH remains above 8.5, the soil solution will contain Al concentrations that would be expected to impair plant growth. Therefore, use of Dicalcium Silicate, or other alkaline product with notable concentrations of soluble Al, presents a risk that is not present in manufactured lime (CaO) or its hydroxide ($Ca(OH)_2$, or in mined limestone.

5.3.5.3 Barium

Total barium (Ba) was enriched in most kiln dusts by as much as 33 times compared to $CaCO_3$ and CaO (Table 7). Montana Limestone LKD had the greatest total Ba content, 862 mg/kg. Kabata-Pendias and Pendias (1984) indicate the total Ba content of surface soils in the United States average 400 to 835 mg/kg depending on soil type and range from 10 to 3000 mg/kg. In soil systems, Ba is relatively insoluble since it I) tends to form precipitates with sulfates and carbonates, and ii) is strongly adsorbed by clays. Therefore, Ba enrichment measured in kiln dust is not expected to impair plant growth.

5.3.5.4 Boron

Total boron (B) was enriched in Greymont LKD (137 mg/kg) and Montana Limestone LKD (130 mg/kg) approximately 50 times compared to control materials (limestone and quicklime, Table 7). Kabata-Pendias and Pendias (1984) indicate total B content of surface soils in the United States average 20 - 55 mg/kg depending on soil type. Holnam CKD had a water extractable B concentration of 5 mg/l while all other alkaline products were below the detection limit. Soil water extractable B concentrations >5 mg/l may impair growth and reproduction of some plant species (Eaton 1944, Munshower 1994). The 5 mg/l B measured in the water extract from the Holnam CKD was at a solution pH of 13.7. Adsorbed (or fixed) B, as opposed to B in the soil solution is highly pH dependent, with maximum adsorption occurring in a pH range of 7 - 9 (Barth et al. 1987). At soil pH > 9.2, $B(OH)_4^-$ predominates in solution and was likely the species measured in LKD. Nonionized $B(OH)_3$ predominates in soil solution in the pH range 7 to 9. Therefore, the amount of B in solution would be less in a pH range of 7.0 - 8.5 compared to a pH of 13.7. Given the solubility characteristics of B, and anticipated alkaline product application rate of less than 10 % of the soil dry weight mass, the enriched levels of water soluble B measured at pH 13.7 are not expected to impair plant growth in an amended soil system having a pH in the range of 7.0 - 8.3.

5.3.5.5 Potassium

Total potassium (K) was enriched in Greymont LKD (137 mg/kg) and Montana Limestone LKD (130 mg/kg) approximately 50 times compared to the control (limestone and quicklime, Table 7). Potassium is an essential plant nutrient and these concentration in alkaline industrial by-products are within the range needed by plants. Therefore, enriched levels of K measured in these alkaline by-products are not expected to impair plant growth.

5.3.5.6 Selenium

Total selenium (Se) was not enriched in alkaline industrial by-products, but the water extract from a saturated paste was enriched several hundred times in CKD compared to the control (Table 7). Holnam and Ash Grove CKD contained 3.31 and 1.30 mg/l Se, respectively, compared to control materials (limestone and quicklime) which had < 0.01 mg/l Se. The primary concern with enriched soil Se levels is that it may facilitate enriched Se concentrations in plant tissues that cause toxic symptoms in livestock as a result of grazing on these plants. Munshower (1994) reported a soil water extractable Se concentration > 0.5 μg/g is considered very enriched (Note 1 μg/g = [1 mg/l]/relative density). Lakin (1972) found certain plant species accumulate sufficient Se to be toxic to animals if soluble soil selenium (selenate, SeO_4^{-2}) concentrations were only a few tenths of a μg/g. Investigators found AB-DTPA extractable soil Se concentrations of < 0.2 μg/g produced plant tissue Se levels greater than levels recommended for prolonged consumption by livestock (Prodgers and Munshower 1991).

At issue is whether 1.30 - 3.31 mg/l Se water extractable measured at a pH of 13.5 - 13.7 in CKD increases- or decreases- in concentration when applied to a soil system and a pH of 7.0 - 8.3 is produced in the plant root zone. Selenate is the predominant form of Se in calcareous soils and selenite is the predominant form in acid soils (Sims et al. 1986). Selenate is highly mobile (i.e. soluble) in alkaline soils. As shown in Figure 4, selenate (SeO_4^{-2}) is the predominant form in an oxidized (i.e. positive Eh) soil system whether the pH is 7.0 or 13.5. Selenite species (H_2SeO_3, $HSeO_3^-$, SeO_3^{-2}) are also present across the pH range 7.0 - 13.5, but these forms of Se are predominant only in a more reduced soil system. Giffen and Shimp (1978) showed that *selenite* solubility decreased from a pH 2 to 9 (Figure 5). Specific information could not be found pertaining to selenate solubility at a pH of 13.5 - 13.7 versus pH 7.0 - 8.3. Therefore, use of CKD to treat acidic-metalliferous soil should be done with caution pertaining to use of selenium accumulating plant species and livestock grazing issues.

5.3.5.7 Zinc

CKD by-products were enriched 12.2 to 25.9 times for total zinc (Zn), while LKD enrichment was 1.3 to 3.8 compared to the control (limestone and quicklime, Table 7). Dicalcium Silicate and Carbide Lime were not enriched in Zn. Ash Grove CKD contained the greatest concentration of total Zn (467 mg/kg), and had the highest water extractable concentration 1.9 mg/l at pH 13.5. Application of this CKD to a soil, followed by carbonation

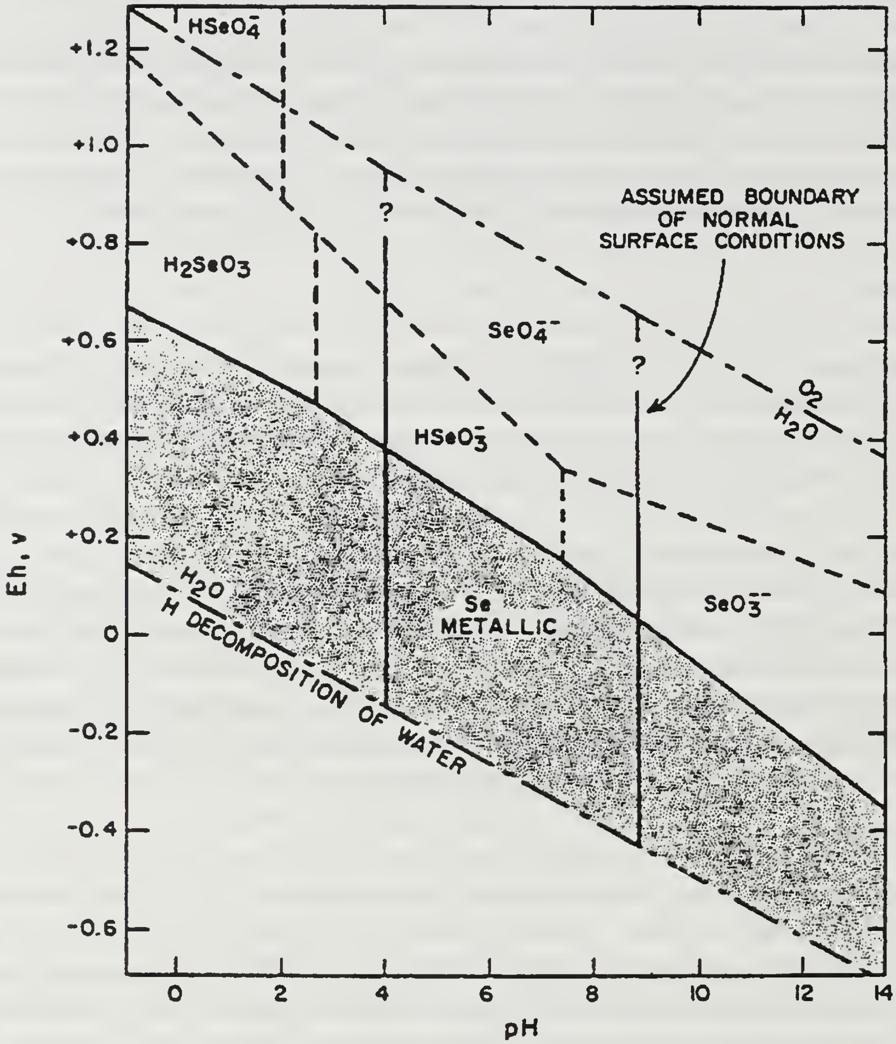


Figure 4. Stable fields of selenium (Brown and Associates 1980, Sims et al. 1986).

Reactions [3] through [7], would result in a soil pH in the range of 7.0 to 8.3. As illustrated in Figure 6, the zinc in the soil solution at pH 13.5 (1.9 mg/l) is predicted to have a lower concentration in an amended soil system, for example pH 7.5, where the Zn concentration in solution would be 0.6 mg/l.

The soil solution concentration of Zn that can cause a phytotoxic response is uncertain. Total Zn concentrations in soil that produce phytotoxic response are usually in the 250 to 650 mg/kg range (Munshower 1994). Kabata-Pendias and Pendias (1984) reviewed results from several investigations and found total soil Zn concentrations of 70 - 400 mg/kg caused phytotoxicity. Kiln dust application rates in the range of 2 - 10 % (dry weight basis) will increase the total Zn concentration in the tailings (used in this investigation, Table 6) approximately 1 %

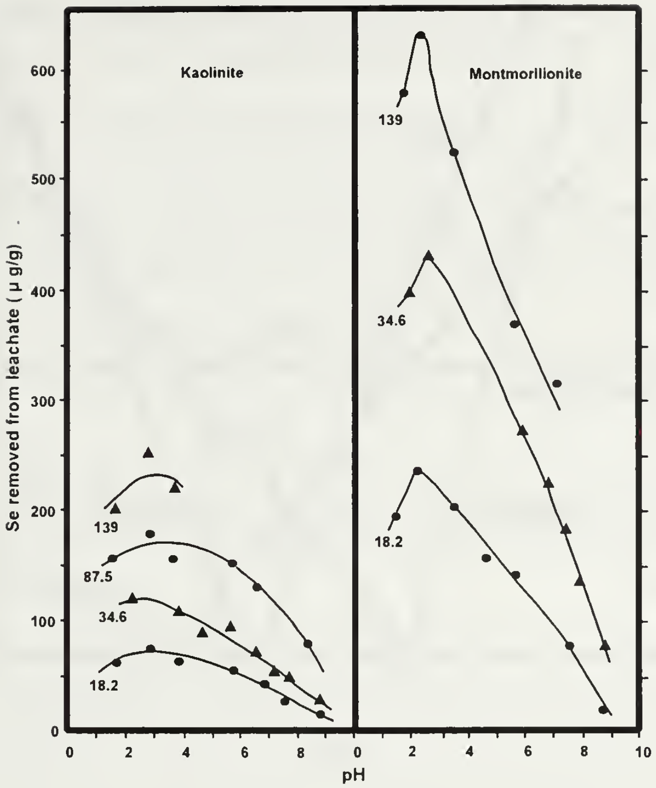


Figure 5. Amount of selenite removed from DuPage leachate solutions by clay minerals as a function of soil pH (from Griffin and Shimp 1978).

to 50 % and in contaminated soil <1 % to 15 %. It is not known whether increased Zn concentration in the soil system due to kiln dust application will exacerbate the phytotoxicity issue, but the risk of impaired plant growth is increased by producing a higher contaminate concentration in the soil system

5.3.5.8 Arsenic, Cadmium, Chromium, Copper, Lead, Manganese, Nickel

In general, both LKD and CKD had enrichment in arsenic, cadmium, chromium, copper, lead, manganese and nickel, compared to lime (CaO) and limestone, while Dicalcium Silicate and Carbide Lime were not enriched in these elements (Table 7). Although the degree of enrichment for these chemical elements was often notable, the final concentration in an amended soil (assuming a 2-10 % amendment application rate, dry weight basis) would be relatively low and is not expected to produce a phytotoxic response. However, use of kiln dust will generally increase the level of these contaminants in the amended soil system and the impact, if any, to plant growth is not known. Given these circumstances, plant growth tests are appropriate to better understand phytotoxicity issues.

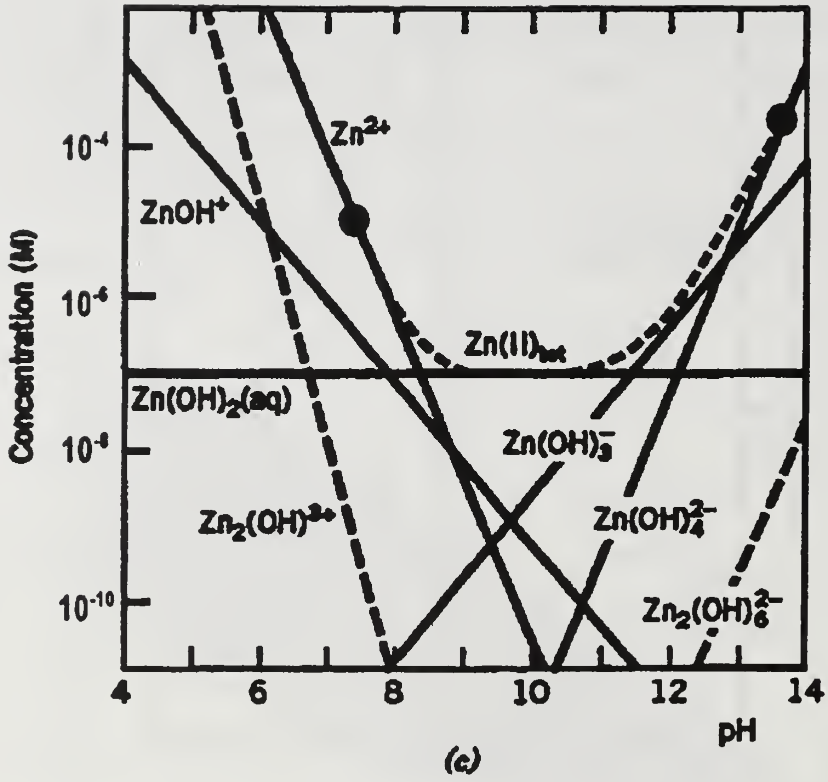


Figure 6. Zinc solubility and chemical form present as a function of pH (from Stumm and Morgan 1996; concentration scale adjusted to known Zn^{+2} concentration for Ash Grove CKD at pH 13.5). Zinc concentration in CKD (1.9 mg/l) is shown as a dot (●) above pH 13.5, and the predicted zinc concentration in an amended soil (0.6 mg/l) is shown as a dot above pH 7.5.

6.0 EFFECT OF ALKALINE INDUSTRIAL BY-PRODUCT ON PLANT GROWTH IN ACIDIC-CONTAMINATED SOIL

6.1 SOIL pH CONTROL DURING THE PLANT GROWTH PERIOD

Addition of alkaline amendments initially raised the soil pH into a range of 9.0 to 12.0 which is not suitable for plant growth. Amended soils were treated with CO_2 gas and water for months to expedite carbonation Reactions [3] through [7], discussed above, to produce a soil with a pH suitable for plant growth (7.0 - 8.4). Once a suitable soil pH was attained and pots were seeded, pH was monitored during the 111 day plant growth period to determine whether the pH of these amended soils remained in the suitable range.

Unamended tailings and the contaminated soil had pH levels of 1.9 - 2.0 and 5.0, respectively, both prior to seeding and after the 111 day plant growth period (Table 12). The unamended Plant Growth Center soil mean pH before and after the 111 day plant growth period ranged from 7.1 - 7.6.

Substrates **amended** with alkaline products were in a suitable range (7.0 - 8.4) during the 111 day plant growth period, with infrequent exceedences of 8.5 and 8.6 (Table 12). Amended soils had a mean pH range of 7.7 - 8.0 for tailings, 7.6 - 8.0 for contaminated soil, and 7.9 - 8.2 for Plant Growth Center soil. During the plant growth period, tailings pH was not significantly different when amended by the various types of alkaline products tested, with one exception. Ash Grove Cement Kiln Dust (CKD) produced a mean pH of 8.0 at the completion of the Basin Wildrye growth period which was greater than the $CaCO_3/CaO$ and Carbide Lime treatments. This elevated pH may have been due to sodium hydrolysis attributed to the presence of excess sodium in CKD [Reaction 8]. Sodium on the clay (micelle) cation exchange undergoes hydrolysis to form hydroxide in the soil solution, a strong base that will raise the pH.

$$Na\boxed{\text{Micelle}} + HOH \rightleftharpoons H\boxed{\text{Micelle}} + Na^{+} + OH^{-} \qquad \text{[Reaction 8]}$$

For the contaminated soil, MT Limestone LKD and Dicalcium Silicate produced significantly greater pH by 0.3 to 0.4 units, compared to $CaCO_3/CaO$, Holnam CKD and Ash Grove CKD for pots containing Basin Wildrye at the completion of the 111 day plant growth period. Similarly, for pots containing Redtop, MT Limestone LKD and Dicalcium Silicate treated soil had significantly higher pH values, 8.0 - 8.1 versus 7.7 - 7.8, compared to several alkaline by-products after the completion of he 111 day plant growth period. For each alkaline product the pH generally changed a few tenths of a unit during the course of the plant growth period, but remained in the suitable range for plant growth.

For the Plant Growth Center soil, alkaline industrial by-products had similar pH levels in plant growth pots at the completion of the 111 day plant growth period compared to $CaCO_3/CaO$. One exception was Holnam (CH_4) CKD, pH 8.4, which was greater than all other treatments. This elevated soil pH may be cause for soil nitrogen, phosphorus and potassium to become less

Table 12. Soil pH in pots containing amended tailings, contaminated soil and Plant Growth Center soil prior to seeding and during the plant growth period.

Amendment Type	pH (s.u.)					
	Basin Wildrye days after seeding			Redtop days after seeding		
	0	70	111	0	70	111
	Tailings					
Greymont LKD	7.7[1]	8.1 b[2]	7.9 bc	7.7	8.2 b	7.7 b
Tacoma LKD	7.9	8.1 b	7.8 bc	7.9	8.1 b	7.7 b
MT Limestone LKD	8.4	8.1 b	7.8 bc	8.4	8.0 b	7.8 b
Holnam (CH_4) CKD	8.1	8.0 b	7.8 bc	8.1	8.0 b	7.8 b
Holnam (Coal, Coke) CKD	7.5	8.2 b	7.8 bc	7.5	8.1 b	7.8 b
Ash Grove CKD	7.6	8.2 b	8.0 ac	7.6	8.2 b	8.0 b
Dicalcium Silicate	8.3	8.1 b	7.8 bc	8.3	8.1 b	7.9 b
Carbide Lime	8.2	8.0 b	7.7 b	8.2	8.1 b	7.8 b
$CaCO_3$/CaO	8.3	8.1 b	7.7 b	8.3	8.0 b	7.8 b
Control	2.0	1.9 a	1.9 a	2.0	2.0 a	1.9 a
	Contaminated Soil					
Greymont LKD	7.7	8.2 bc	7.7 bcd	7.7	8.2 bc	7.9 bc
Tacoma LKD	8.2	8.3 cd	7.8 bcd	8.2	8.4 d	7.7 b
MT Limestone LKD	8.4	8.5 d	8.0 d	8.4	8.3 cd	8.0 c
Holnam (CH_4) CKD	7.8	8.1 b	7.7 bc	7.8	8.1 bc	7.7 b
Holnam (Coal, Coke) CKD	8.1	8.1 b	7.7 bc	8.1	8.1 bc	7.7 b
Ash Grove CKD	8.3	8.1 b	7.6 b	8.3	8.1 bc	7.7 b
Dicalcium Silicate	8.3	8.1 b	7.9 cd	8.3	8.0 b	8.1 c
Carbide Lime	8.1	8.4 cd	7.9 cd	8.1	8.4 d	7.9 bc
$CaCO_3$/CaO	7.9	8.3 cd	7.6 b	7.9	8.3 cd	7.8 b
Control	5.0	5.1 a	5.0 a	5.0	4.9 a	5.0 a
	Plant Growth Center Soil					
Greymont LKD	7.8	8.1 a	7.9 b	7.8	8.3 a	7.9 b
Tacoma LKD	7.8	8.5 b	8.0 bc	7.8	8.5 a	8.3 c
MT Limestone LKD	8.1	8.3 b	8.2 bc	8.1	8.2 a	8.2 bc
Holnam (CH_4) CKD	7.7	8.5 b	8.4 d	7.7	8.4 a	8.3 c
Holnam (Coal, Coke) CKD	7.6	8.4 b	8.0 bc	7.6	8.4 a	8.0 bc
Ash Grove CKD	7.6	8.4 b	8.0 bc	7.6	8.5 a	8.0 bc
Dicalcium Silicate	8.3	8.6 b	8.0 bc	8.3	8.6 a	8.1 bc
Carbide Lime	7.8	8.4 b	8.0 bc	7.8	8.6 a	8.1 bc
$CaCO_3$/CaO	7.6	8.5 b	8.1 bc	7.6	8.3 a	8.1 bc
Control	7.6	8.3 b	7.1 a	7.6	8.2 a	7.3 a

[1] These pH values (n = 1) for time zero, i.e. prior to seeding, were taken in the bulk sample barrel used to prepare the substrate for greenhouse pots.
[2] Means (n = 8) followed by the same letter in the same column are not significantly different (P = 0.05).

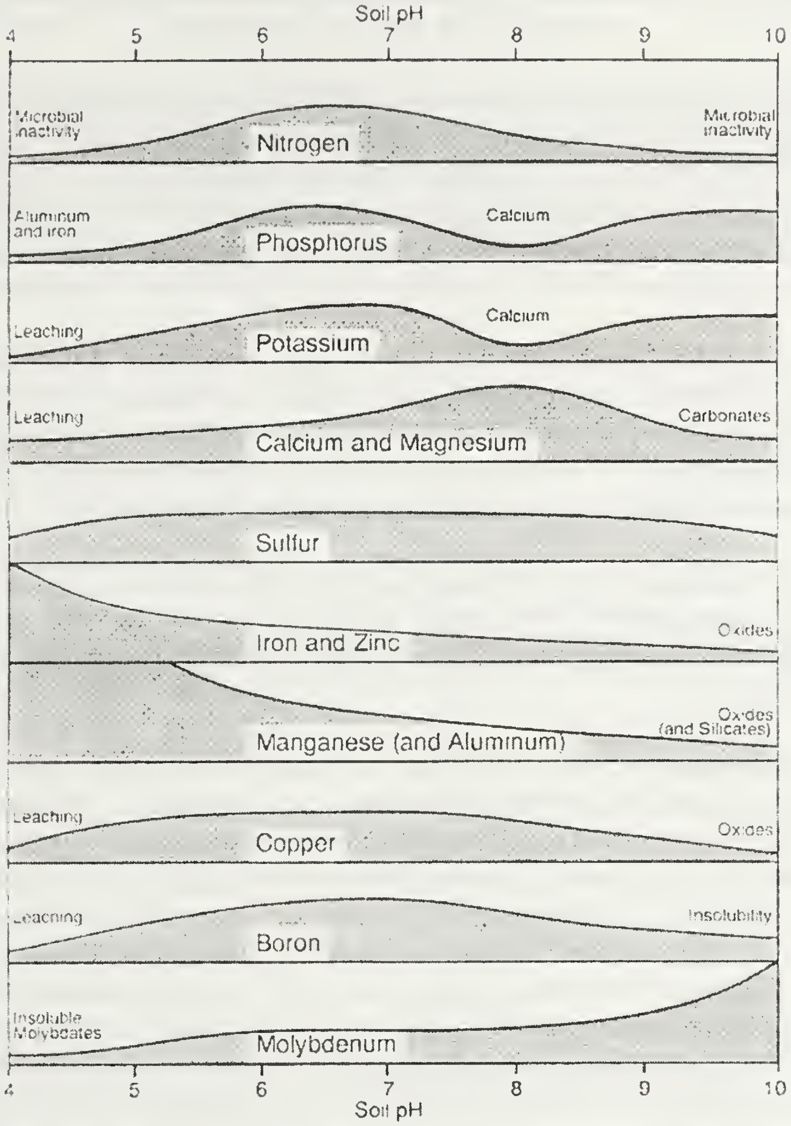


Figure 7. Effect of soil pH on plant availability of metals and nutrients in the soil solution (Troeh and Thompson 1993).

available for plant uptake, compared to a soil pH range of 7.0 to 8.0 (Figure 7). For this reason, plant growth may be enhance in pots that maintain a soil pH< 8.0 compared to those with pH >8.0.

6.2 EFFECT OF ALKALINE INDUSTRIAL BY-PRODUCTS ON INITIAL 14 DAYS OF PLANT GROWTH

Percent seed germination for Basin Wildrye and Redtop was not significantly different between pots amended with different alkaline industrial products (Tables 13 and 14). Seeds did not germinate in tailings that were not amended with an alkaline product. In pots amended with alkaline products, Basin Wildrye had a mean percent germination of 69.8±6.6 and Redtop 91.6± 4.7 in tailings and contaminated soil . Mean percent germination in amended pots containing Plant Growth Center soil was 77.6±7.5 for Basin Wildrye and 91.0±6.5 for Redtop.

The number of days required for seedlings to emerge for Basin Wildrye and Redtop was not significantly different between pots amended with different alkaline industrial products (Tables 13 and 14). Seedling emergence occurred within 5 to 8 days following planting in either tailings or contaminated soil. Time required for plant emergence in amended pots that had Plant Growth Center soil was similar to that for tailings and contaminated soil.

Of the plant seedlings that emerged, all survived after 14 days of growth in tailings and contaminated soil when amended with alkaline products (Tables 13 and 14). Consequently, there were no significant differences between alkaline products regarding seedling survival for Basin Wildrye and Redtop.

After 14 days of growth, **Basin Wildrye** had a significantly greater plant shoot height in tailings amended with either of the Holnam CKD products compared to MT Limestone LKD, but these were not different compared to other alkaline products (Table 13). Greater shoot height after 14 days generally corresponds to greater root mass that can facilitate plant survival under harsh growing conditions. Conversely, a slow developing shoot will have less root development and may be more adversely affected by harsh environmental factors such as lack of water. In the contaminated soil, Basin Wildrye shoot height after 14 days was significantly greater for all pots amended with alkaline industrial products compared to no treatment (control). Apparently the acidic (pH 5.0) metal contaminated soil condition impaired seedling development. In the Plant Growth Center soil, the $CaCO_3$/CaO and Tacoma LKD treatments had a significantly greater Basin Wildrye shoot height compared to the MT Limestone LKD treatment, but these were not different compared to other alkaline products. Basin Wildrye mean shoot height was numerically greatest for the Plant Growth Center soil (110.6 mm) compared to that for tailings (90.7 mm) and the contaminated soil (106.0 mm).

After 14 days of growth, **Redtop** shoot height was not significantly different in pots containing tailings amended with alkaline industrial products (Table 14). In pots containing the contaminated soil, Redtop shoot height was not significantly different for the various alkaline industrial products tested. However, pots containing the **unamended** contaminated soil had significantly less shoot length compared to all pots that were amended with alkaline products.

Table 13. Effect of different alkaline products on growth of Basin Wildrye during the initial 14 days.

Amendment Type	Time to Emergence (days)	Germination %	Survival %	Shoot Height (mm)
	Tailings			
Greymont LKD	7.1 a[1]	73.3 a	100.0 a	88.9 ab
Tacoma LKD	7.1 a	71.3 a	100.0 a	94.2 ab
MT Limestone LKD	7.1 a	65.3 a	100.0 a	78.4 b
Holnam (CH_4) CKD	6.5 a	78.7 a	100.0 a	100.5 a
Holnam (Coal,Coke)	7.0 a	64.0 a	100.0 a	103.5 a
Ash Grove CKD	8.0 a	74.7 a	100.0 a	85.1 ab
Dicalcium Silicate	6.5 a	65.3 a	100.0 a	86.5 ab
Carbide Lime	6.7 a	83.3 a	100.0 a	86.7 ab
$CaCO_3$/CaO	6.3 a	75.3 a	100.0 a	92.7 ab
Control	None	0.0 b	None	None
	Contaminated Soil			
Greymont LKD	6.6 a	70.0 a	100.0 a	99.8 a
Tacoma LKD	6.3 a	70.0 a	100.0 a	101.4 a
MT Limestone LKD	6.5 a	68.0 a	100.0 a	107.2 a
Holnam (CH_4) CKD	6.6 a	74.7 a	100.0 a	107.5 a
Holnam (Coal,Coke)	6.5 a	74.0 a	100.0 a	110.7 a
Ash Grove CKD	6.6 a	65.3 a	100.0 a	96.9 a
Dicalcium Silicate	6.3 a	68.0 a	100.0 a	111.7 a
Carbide Lime	6.6 a	58.7 a	100.0 a	109.7 a
$CaCO_3$/CaO	5.6 a	57.3 a	100.0 a	109.1 a
Control	7.2 a	64.7 a	100.0 a	38.1 b
	Plant Growth Center Soil			
Greymont LKD	5.8 ab	88.7 a	100.0 a	108.9 ab
Tacoma LKD	6.6 ab	80.0 a	100.0 a	122.2 a
MT Limestone LKD	6.3 ab	68.7 a	100.0 a	100.1 b
Holnam (CH_4) CKD	6.6 ab	76.7 a	100.0 a	112.6 ab
Holnam (Coal,Coke)	6.0 ab	82.0 a	100.0 a	99.4 b
Ash Grove CKD	6.6 ab	70.0 a	100.0 a	108.4 ab
Dicalcium Silicate	6.8 a	70.7 a	100.0 a	105.7 ab
Carbide Lime	5.7 ab	88.0 a	100.0 a	114.3 ab
$CaCO_3$/CaO	5.8 ab	74.0 a	100.0 a	124.2 a
Control	5.3 b	87.3 a	100.0 a	117.2 ab

[1] Means (n = 8) followed by the same letter in the same column for each substrate are not significantly different (P=0.05).

Table 14. Effect of different alkaline products on growth of Redtop during the initial 14 days.

Amendment Type	Time to Emergence (days)	Germination %	Survival %	Shoot Height (mm)
		Tailings		
Greymont LKD	6.2 a[1]	91.3 a	100.0 a	24.2 a
Tacoma LKD	6.6 a	88.7 a	100.0 a	28.2 a
MT Limestone LKD	6.3 a	94.7 a	100.0 a	19.7 a
Holnam (CH_4) CKD	6.2 a	92.0 a	100.0 a	23.2 a
Holnam (Coal,Coke)CKD	5.8 a	94.0 a	100.0 a	29.8 a
Ash Grove CKD	6.3 a	92.0 a	100.0 a	21.7 a
Dicalcium Silicate	5.6 a	94.7 a	100.0 a	26.9 a
Carbide Lime	5.7 a	91.3 a	100.0 a	22.5 a
$CaCO_3$/CaO	5.7 a	92.0 a	100.0 a	28.3 a
Control	None	0.0 b	None	None
		Contaminated Soil		
Greymont LKD	5.8 b	86.0 a	100.0 a	31.1 a
Tacoma LKD	5.7 b	90.0 a	100.0 a	32.3 a
MT Limestone LKD	5.7 b	93.3 a	100.0 a	32.0 a
Holnam (CH_4) CKD	6.0 b	93.3 a	100.0 a	27.6 a
Holnam (Coal,Coke)CKD	6.3 b	76.6 a	100.0 a	28.6 a
Ash Grove CKD	5.8 b	92.0 a	100.0 a	36.3 a
Dicalcium Silicate	5.7 b	94.0 a	100.0 a	33.6 a
Carbide Lime	6.1 b	83.3 a	100.0 a	32.4 a
$CaCO_3$/CaO	6.0 b	90.6 a	100.0 a	27.7 a
Control	8.5 a	12.5 b	100.0 a	9.6 b
		Plant Growth Center Soil		
Greymont LKD	5.5 a	96.7 a	100.0 a	42.3 b
Tacoma LKD	5.5 a	94.0 a	100.0 a	52.8 a
MT Limestone LKD	5.7 a	84.0 a	100.0 a	31.3 cd
Holnam (CH_4) CKD	5.3 a	90.7 a	100.0 a	42.9 b
Holnam (Coal,Coke)CKD	6.1 a	94.0 a	100.0 a	29.6 d
Ash Grove CKD	5.8 a	77.3 a	100.0 a	44.9 b
Dicalcium Silicate	5.6 a	94.7 a	100.0 a	39.9 bc
Carbide Lime	5.6 a	90.7 a	100.0 a	38.6 bc
$CaCO_3$/CaO	5.5 a	97.3 a	100.0 a	58.5 a
Control	5.5 a	100.0 a	100.0 a	61.5 a

[1] Means (n = 8)followed by the same letter in the same column for each substrate are not significantly different (P=0.05).

Apparently, this soil with pH 5.0 and enriched levels of metals caused decreases plant shoot development during the initial 14 days. The Plant Growth Center soil had significantly greater plant shoot height for the control, $CaCO_3$/CaO, and Tacoma LKD treatments compared to other alkaline products. Conversely, treatment with Holnam (Coke,Coal) CKD resulted in significantly less plant shoot height compared to all other alkaline products. These results indicate nearly all alkaline by-products impaired growth of Redtop in the Plant Growth Center soil during the first 14 days of seedling development. Redtop mean shoot height was numerically greatest for the Plant Growth Center soil (42.3 mm) compared to that for tailings (24.9 mm) and the contaminated soil (31.3 mm).

In summary, when acidic-metalliferous tailings was not amended with an alkaline product, there was no plant growth. When acidic contaminated soil was not amended with an alkaline product, plant shoot height after 14 days was significantly impaired. Alkaline industrial products did not impair either seed germination, plant emergence or plant survival after 14 days of growth. In general, treatment of tailings and contaminated soil with any one of these alkaline products facilitated acceptable plant growth after 14 days. Initial plant growth in $CaCO_3$/CaO amended soil systems was similar to that attained by CKD and LKD products, Dicalcium Silicate, and Carbide Lime.

6.3 EFFECT OF ALKALINE INDUSTRIAL BY-PRODUCTS AFTER 111 DAYS OF PLANT GROWTH

Following a 111 day growth period, Basin Wildrye and Redtop were harvested and measurements were made for above ground plant biomass, plant height, root biomass, maximum root depth, and number of roots at the 5 cm and 10 cm soil depths. Representative above ground and below ground growth of Basin Wildrye and Redtop as a function of the different alkaline products tested are shown in Figures 8 and 9.

6.3.1 Above Ground Plant Biomass

In **tailings**, no plant growth was present when an alkaline product was not applied and the pH remained ≤ 2.0 (Tables 15 and 16). Two LKD products (Greymont, Tacoma) and Dicalcium Silicate produced the greatest numerical values for above ground Basin Wildrye biomass and were significantly greater compared to several alkaline products ($CaCO_3$/CaO, MT Limestone LKD, Ash Grove CKD, Carbide Lime). For Redtop, Tacoma LKD, Holnam (Coke, Coal) CKD, and Dicalcium Silicate had the greatest numerical values for above ground production and were significantly greater than several alkaline products ($CaCO_3$/CaO, MT Limestone LKD, Ash Grove CKD, Carbide Lime).

In **contaminated soil**, above ground biomass was generally increased by each alkaline product tested, indicating the unamended soil pH of 5.0 impaired plant growth. Above ground biomass for Basin Wildrye was numerically greatest for soil amended with the three LKD products but they were not significantly different compared to other alkaline industrial

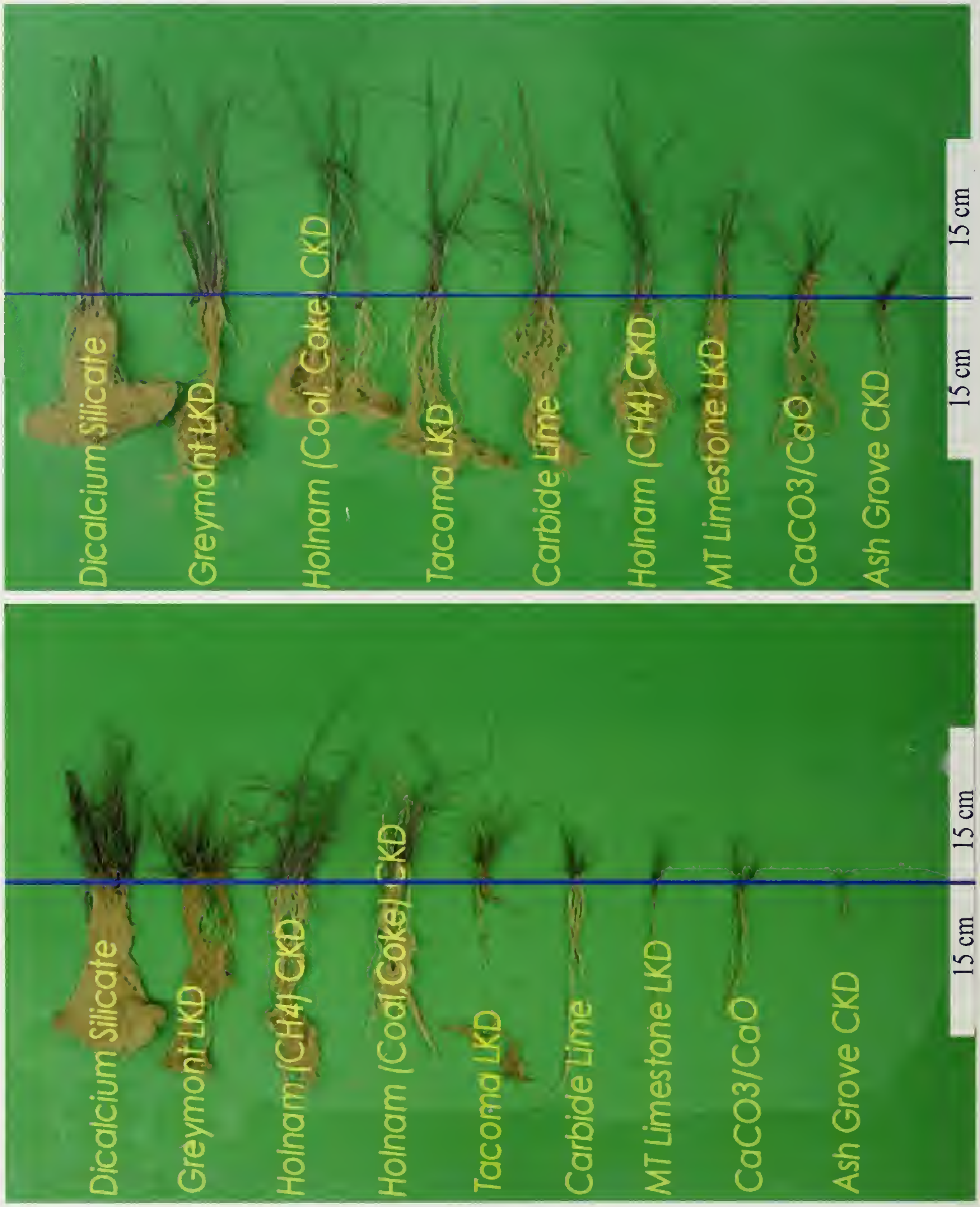


Figure 8. Photos of Basin Wildrye (top) and Redtop (bottom) after a 111 day plant growth period in **tailings** as a function of different alkaline products.

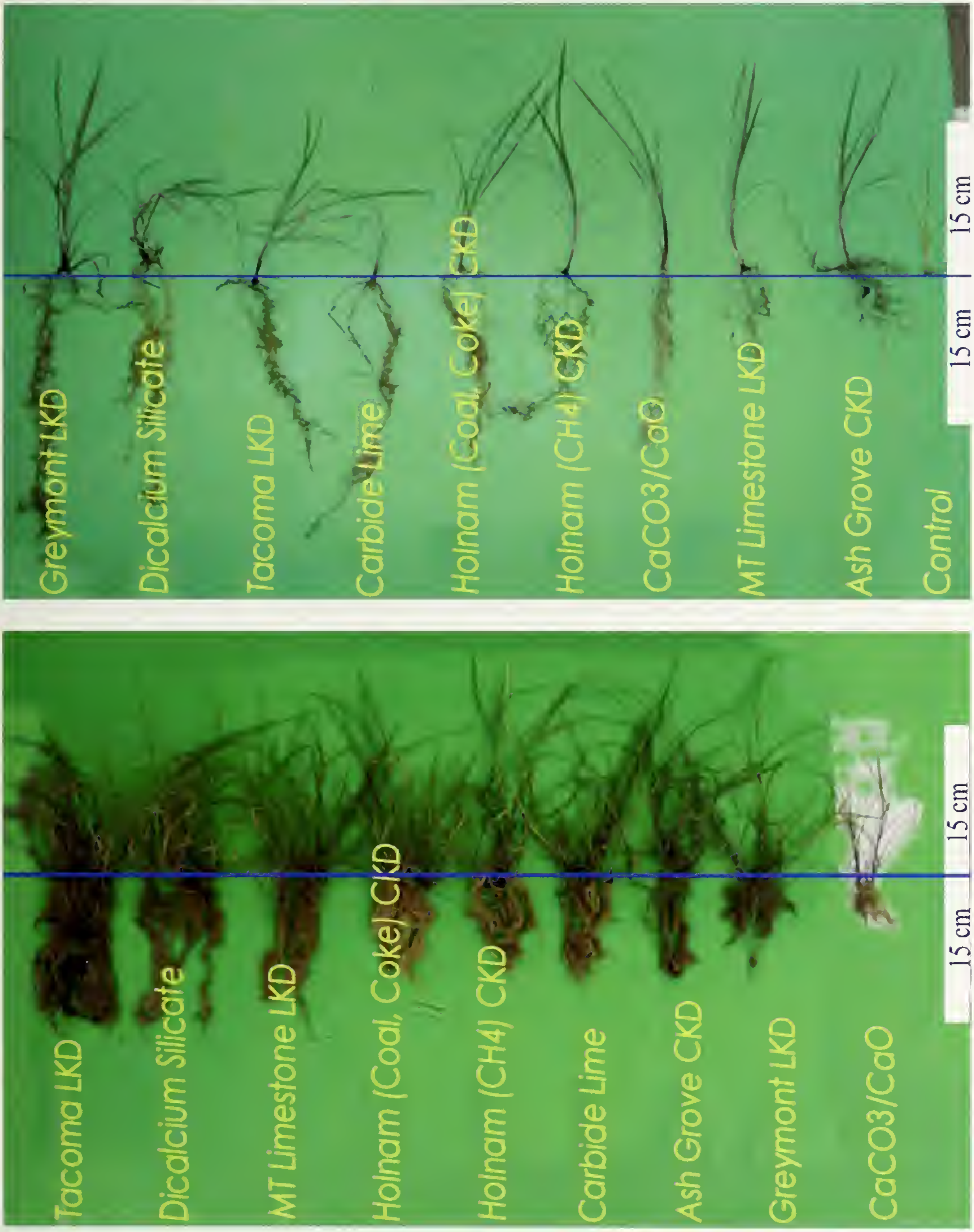


Figure 9. Photos of Basin Wildrye (top) and Redtop (bottom) after a 111 day plant growth period in **contaminated soil** as a function of different alkaline products.

Table 15. Effect of different alkaline products on growth of Basin Wildrye 111 days after seeding.

Amendment Type	Above Ground Height (mm)	Maximum Root Depth (mm)[2]	Number of Roots 5 cm Depth	Number of Roots 10 cm Depth	Above Ground Biomass (g)	Below Ground Biomass (g)
	Tailings					
Greymont LKD	254.5 ab[1]	116.2	15.2 bc	21.3 bc	0.492 a	0.969 ab
Tacoma LKD	293.0 a	126.5	21.8 ab	26.6 b	0.547 a	1.325 a
MT Limestone LKD	159.0 b	118.0	15.0 bc	19.7 bc	0.193 bc	0.526 b
Holnam (CH_4) CKD	224.1 ab	139.7	16.3 bc	28.3 b	0.31abc	0.467 b
Holnam (Coal,Coke)CKD	339.5 a	105.3	25.2 ab	37.0 b	0.397 ab	0.922 ab
Ash Grove CKD	157.0 b	109.6	9.6 c	8.6 c	0.143 bc	0.268 b
Dicalcium Silicate	319.1 a	121.7	55.8 a	74.3 a	0.566 a	1.482 a
Carbide Lime	172.7 b	109.5	15.1 bc	10.6 bc	0.152 bc	0.299 b
$CaCO_3$/CaO	141.4 b	109.7	8.8 c	10.8 bc	0.068 c	0.261 b
Control	None	None	None	None	None	None
	Contaminated Soil					
Greymont LKD	271.5 a	105.0	16.0 bc	12.0 ab	0.620 a	0.646 ab
Tacoma LKD	257.4 a	117.6	44.6 a	31.8 a	0.616 a	0.934 a
MT Limestone LKD	242.5 a	110.6	22.5 b	17.2 ab	0.530 ab	0.717 ab
Holnam (CH_4) CKD	233.6 a	111.7	25.0 b	18.2 ab	0.495 ab	0.844 ab
Holnam (Coal,Coke)CKD	212.7 a	113.3	24.7 b	19.7 ab	0.423 ab	0.461 abc
Ash Grove CKD	174.0 a	103.1	19.5 bc	11.3 b	0.447 ab	0.358 abc
Dicalcium Silicate	229.9 a	99.2	17.7 bc	14.3 ab	0.417 abc	0.556 abc
Carbide Lime	190.9 a	97.3	17.7 bc	4.2 c	0.262 bc	0.452 abc
$CaCO_3$/CaO	174.6 a	92.1	12.3 bc	2.1 c	0.232 bc	0.258 c
Control	76.2 b	17.9	0.2 c	0.0 c	0.073 c	0.023 c
	Plant Growth Center Soil					
Greymont LKD	548.2 a	116.8	75.1 ab	84.6 b	2.248 a	4.829 ab
Tacoma LKD	591.8 a	103.0	62.5 b	95.6 b	2.809 a	4.645 ab
MT Limestone LKD	477.1 ab	118.6	51.8 b	80.6 b	1.192 b	3.307 abc
Holnam (CH_4) CKD	415.1 b	110.5	44.8 b	46.8 b	1.170 b	2.642 cd
Holnam (Coal,Coke)CKD	500.0 ab	122.6	43.5 b	87.7 b	1.992 ab	4.527 abc
Ash Grove CKD	414.2 b	114.2	36.2 b	52.5 b	1.147 b	2.132 d
Dicalcium Silicate	483.1 ab	106.8	53.1 b	96.8 b	1.230 b	3.114 c
Carbide Lime	505.6 ab	105.7	45.0 b	61.8 b	2.291 a	3.537 c
$CaCO_3$/CaO	520.9 ab	103.2	42.2 b	39.5 b	2.238 a	3.812 abc
Control	507.7 ab	113.0	98.7 a	159.3 a	2.204 a	6.715 a

[1] Means (n = 8) followed by the same letter in the same column for each substrate are not significantly different (P=0.05).

[2] Plant roots grew to the bottom of every pot when treated with an alkaline amendment. Differences in maximum root depth are due to different soil depths between pots due to settling.

Table 16. Effect of different alkaline products on growth of Redtop 111 days after seeding.

Amendment Type	Above-ground Height (mm)	Maximum [2] Root Depth (mm)	Number of Roots 5 cm Depth	Number of Roots 10 cm Depth	Above-ground Biomass (g)	Below-ground Biomass (g)
Tailings						
Greymont LKD	148.8abc[1]	96.1	24.5 b	25.6 b	0.389 ab	0.566 c
Tacoma LKD	200.2 a	126.8	29.9 ab	38.5 b	0.935 a	1.793 a
MT Limestone LKD	120.3 bc	118.7	21.7 b	19.5 b	0.128 b	0.296 c
Holnam (CH_4) CKD	151.3 abc	117.7	21.1 b	21.2 b	0.310 ab	0.467 c
Holnam (Coal,Coke) CKD	210.5 a	110.2	29.1 ab	38.6 b	0.663 a	0.980 bc
Ash Grove CKD	108.0 c	111.0	12.2 b	6.6 b	0.106 b	0.150 c
Dicalcium Silicate	187.1 ab	119.1	47.9 a	74.5 a	0.621 a	1.385 ab
Carbide Lime	84.3 c	104.3	12.1 b	3.7 b	0.089 b	0.164 c
$CaCO_3$/CaO	102.1 c	105.7	11.7 b	6.8 b	0.180 b	0.108 c
Control	None	None	None	None	None	None
Contaminated Soil						
Greymont LKD	197.8 bc	100.0	18.3 b	6.2 bcd	0.370 bc	0.424 b
Tacoma LKD	374.8 a	119.0	49.6 a	63.5 a	1.341 a	1.314 a
MT Limestone LKD	286.8 b	113.2	27.7 ab	25.8 ab	0.825 b	0.608 b
Holnam (CH_4) CKD	273.1 bc	105.5	35.0 ab	32.1 ab	0.630 bc	0.719 b
Holnam (Coal,Coke) CKD	230.6 bc	110.6	30.2 ab	35.1 ab	0.703 bc	0.837 b
Ash Grove CKD	223.6 bc	99.8	15.1 b	13.1 bc	0.460 bc	0.340 b
Dicalcium Silicate	252.1 bc	103.5	30.3 ab	23.8 ab	0.784 b	0.793 b
Carbide Lime	234.0 bc	111.5	34.7 ab	18.3 bc	0.365 bc	0.356 b
$CaCO_3$/CaO	160.1 c	71.2	12.7 b	5.1 cd	0.198 c	0.362 b
Control	7.7 d	14.8	0.0 c	0.0 d	0.031 c	0.021 b
Plant Growth Center Soil						
Greymont LKD	345.3 a	119.1	48.8 a	67.5 bc	2.587 a	3.794 b
Tacoma LKD	335.0 a	105.3	70.6 a	102.5ab	2.763 a	3.276 b
MT Limestone LKD	355.8 a	131.8	65.0 a	63.1 bc	2.004 ab	3.013 b
Holnam (CH_4) CKD	284.5 ab	115.3	43.1 a	69.0 bc	1.573 ab	3.308 b
Holnam (Coal,Coke) CKD	298.7 ab	122.1	60.0 a	102.5ab	2.305 a	3.287 b
Ash Grove CKD	248.5 b	113.3	48.6 a	44.8 c	1.025 b	1.721 b
Dicalcium Silicate	285.0 ab	105.0	50.6 a	55.0 c	1.581 ab	2.732 b
Carbide Lime	327.2 a	111.2	48.7 a	32.2 c	2.561 a	2.004 b
$CaCO_3$/CaO	329.2 a	103.8	46.0 a	40.5 c	2.673 a	2.784 b
Control	301.7 ab	114.1	75.6 a	115.6 a	1.989 ab	6.395 a

[1] Means (n = 8)followed by the same letter in the same column for each substrate are not significantly different (P=0.05).

[2] Plant roots grew to the bottom of every pot when treated with an alkaline amendment. Differences in maximum root depth are due to different soil depths between pots due to settling.

by-products. Treatment with two LKD products (Greymont and Tacoma) had significantly greater Basin Wildrye biomass compared to treatment with the $CaCO_3/CaO$ mixture. Redtop biomass was greatest for soils amended with Tacoma LKD. Two alkaline by-products (MT Limestone LKD and Dicalcium Silicate) produced significantly greater biomass compared to the $CaCO_3/CaO$ mixture.

When alkaline products were applied to the **Plant Growth Center soil**, average above ground biomass of Basin Wildrye was 568 % greater than that for tailings and 404 % greater than that for contaminated soil. Redtop above ground biomass in amended Plant Growth Center soil was 535 % greater than that for tailings and 336 % greater than that for the contaminated soil. These results illustrate that raising the pH in tailings and the contaminated soil enables significantly improved plant growth, but these contaminated mediums will not provide optimum plant growth attained in a high quality soil medium. The Plant Growth Center soil was composed of 33 % Bozeman silt loam, 33 % sand, and 33 % sphagnum peat.

In summary, all alkaline industrial by-products tested resulted in above ground biomass equal to- or greater than- that attained with $CaCO_3/CaO$. Treatment with the mixture 60 % $CaCO_3$ and 40 % CaO (weight basis) has been the recommended approach to neutralize acidic-contaminated soil systems.

6.3.2 Above Ground Height

In **tailings**, three alkaline by-products (Tacoma LKD, Holnam (Coke,Coal) CKD, Dicalcium Silicate) produced the greatest numerical values for Basin Wildrye and Redtop height and each was significantly greater than treatment with three alkaline products ($CaCO_3/CaO$, Ash Grove CKD, Carbide Lime) (Tables 15 and 16).

In **contaminated soil**, all alkaline products produced significantly greater plant height compared to the unamended control which had a pH 5.0. Plant height for Basin Wildrye was not different between alkaline products tested. For Redtop, significantly greater plant height was attained with Tacoma LKD compared to all other treatments. Treatment with Tacoma LKD and MT Limestone LKD had significantly greater plant height compared to treatment with the $CaCO_3/CaO$ mixture.

In summary, all alkaline industrial by-products tested resulted in plant height equal to- or greater than- that attained with the $CaCO_3/CaO$ mixture.

6.3.3 Below Ground Biomass

In **tailings**, treatment with two alkaline by-products (Tacoma LKD, Dicalcium Silicate) resulted in numerically the largest Basin Wildrye root mass, and each was significantly greater than other alkaline products tested except for Greymont LKD and Holnam (Coke, Coal) CKD

(Table 15). Tacoma LKD and Dicalcium Silicate also produced significantly more Redtop root biomass compared to other alkaline products, except Holnam (Coke, Coal) CKD (Table 16).

In **contaminated soil**, all alkaline products had numerical values for root mass notably greater compared to the control which had a pH 5.0. Treatment with Tacoma LKD resulted in the greatest numerical value for Basin Wildrye root mass, but this was not significantly different compared to other alkaline industrial by-products. However, four of eight alkaline industrial by-products had significantly greater root mass compared to the $CaCO_3/CaO$ mixture. For Redtop, soil treatment with Tacoma LKD produced significantly greater root mass compared to other alkaline products.

When alkaline products were applied to the **Plant Growth Center soil**, average root biomass of Basin Wildrye was 500 % greater than that for tailings and 623 % greater than that for contaminated soil. Redtop above ground biomass in amended Plant Growth Center soil was 438 % greater than that for tailings and 450 % greater than that for the contaminated soil. These results illustrate that raising the pH in tailings and the contaminated soil enables significantly improved root development, but these contaminated mediums will not provide optimum root growth attained in a soil without contamination and a high organic matter content.

In summary, all alkaline industrial by-products tested resulted in root biomass equal to- or greater than- that attained with the $CaCO_3/CaO$ mixture. Application of Tacoma LKD consistently produced the largest root biomass values and the difference compared to other alkaline amendments was frequently significant.

6.3.4 Maximum Root Depth

Soil conditions that enable plants to root deep provide a greater reservoir of soil water and nutrients. Conversely, soil physicochemical traits that preclude development of deep roots may impair plant growth.

In **tailings** and **contaminated soil** treated with an alkaline product, roots grew to the bottom of the pot so there were no significant differences regarding maximum root depth. In unamended tailings no roots developed. In unamended contaminated soil maximum root depth was notably less than the depth of the potting soil.

In summary, all alkaline industrial by-products tested resulted in development of maximum plant root depths equal to that attained with the $CaCO_3/CaO$ mixture.

6.3.5 Number of Roots

The greater the number of roots at the 5 cm and 10 cm soil depth the greater the opportunity for the plant to uptake water and nutrients. Also, abundant roots aid in soil structural

development that facilitates stability and infiltration of surface water. Conversely, if the number of roots are few then plant growth and survival may be impaired.

In **tailings**, treatment with DiCalcium Silicate resulted in the largest number of Basin Wildrye roots at the 5 cm depth which was significantly greater than nearly all other alkaline products tested (Table 15). Similarly, the 10 cm soil depth, treatment with Dicalcium Silicate resulted in a significantly greater number of Basin Wildrye roots compared to other treatments. The number of Redtop roots at the 5 cm and 10 cm soil depth was significantly greater for Dicalcium Silicate compared to all other alkaline products (Table 16).

In **contaminated soil**, treatment with all alkaline products resulted in notably larger mean root count numbers at the 5 cm and 10 cm soil depths compared to the control which had a pH 5.0. Soil treatment with Tacoma LKD resulted in a significantly greater number of Basin Wildrye roots at the 5 cm and 10 cm soil depths compared to the $CaCO_3/CaO$ mixture, but was generally not different compared to other alkaline industrial by-products. At the 10 cm soil depth, the number of Basin Wildrye roots was significantly less when soil was amended with either $CaCO_3/CaO$ or Carbide Lime compared to other alkaline products. The number of Redtop roots at the 5 cm and 10 cm depth was significantly greater for soil treated with Tacoma LKD compared to Greymont LKD, Ash Grove CKD, and $CaCO_3/CaO$.

In summary, all alkaline industrial by-products tested resulted in development of plant root numbers at the 5 cm and 10 cm soil depths equal to- or greater than- that attained with the $CaCO_3/CaO$ mixture. Tailings and contaminated soil treated with alkaline product had mean number of roots at the 5 cm and 10 cm depths greater than when these acidic substrates were not amended.

6.4 SUMMARY AND DISCUSSION OF PLANT GROWTH WITH SOILS AMENDED WITH ALKALINE PRODUCTS

Following a 111 day plant growth period for Basin Wildrye and Redtop all alkaline industrial by-products tested had plant growth equal to-or greater than- the $CaCO_3/CaO$ mixture. This was the case for above ground plant biomass, plant height, root biomass, root depth, and number of roots at the 5 cm and 10 cm soil depths. A ranking procedure was used to summarize these results (Table 17). This ranking procedure indicated soil treatment with Tacoma LKD produced the most above and below ground biomass followed closely by treatment with Dicalcium Silicate. Greymont LKD, MT Limestone LKD, and both Holnam CKD products each produced good above and below ground plant biomass, but somewhat less than with Tacoma LKD and Dicalcium Silicate. Treatment with the $CaCO_3/CaO$ mixture, Ash Grove CKD, and Carbide Lime produced the least plant biomass and were ranked the lowest among the alkaline products tested. Acidic-metalliferous tailings and soil not amended with an alkaline product had either poor plant growth or none.

Table 17. Rank of alkaline products to facilitate growth of Basin Wildrye and Redtop in tailings and contaminated soil.

Amendment Type	**Mean Above-ground Biomass [2] (g)**	**Mean Below-ground Biomass [3] (g)**	**Average[4]**	**Rank [1]**
Greymont LKD	0.47	0.65	0.56	**4**
Tacoma LKD	0.86	1.34	1.10	**1**
MT Limestone LKD	0.42	0.54	0.48	**6**
Holnam (CH_4) CKD	0.44	0.62	0.53	**5**
Holnam (Coal,Coke)	0.55	0.80	0.67	**3**
Ash Grove CKD	0.29	0.28	0.28	**7**
Dicalcium Silicate	0.60	1.05	0.83	**2**
Carbide Lime	0.22	0.31	0.27	**8**
$CaCO_3$/CaO	0.17	0.25	0.21	**9**
Control	0.02	0.006	0.14	**10**

[1] Ranking Procedure. For each treatment, mean above ground biomass[2] for Basin Wildrye and Redtop in tailings and contaminated soil was averaged with mean below ground biomass[3] for Basin Wildrye and Redtop in tailings and contaminated soil. This average[4] was ranked 1 through 10 with number 1 being the treatment that produced the greatest plant biomass.

Treatment with the mixture 60 % $CaCO_3$ and 40 % CaO (weight basis) has been the recommended approach to neutralize acidic-contaminated soil systems in the Anaconda-Butte, MT. project area. Apparently, highly enriched concentrations of soluble salts in CKD was not sufficient to impair above ground plant biomass under environmental conditions where water was not a limiting factor. Certain alkaline industrial by-products were highly enriched in various metals (Al, As, Ba, B, Cd, Cu, Pb, Mn, Ni, Se, V, Zn). As discussed in Section 5.0, I) alkaline product dilution with application rates of 2 - 10 % of the soil mass, and ii) low water solubility of these metals of concern in the soil pH range of 7.0 - 8.4 indicated the impact of these contaminates may not be notable; but uncertainty was present. These plant growth tests address this uncertainty and indicate enriched soluble salts and metals in industrial by-products did not cause impairment of plant growth. This issue is discussed in more detail below.

It was not expected that the $CaCO_3$/CaO mixture would produce significantly less plant growth compared to alkaline industrial by-products, as was often the case. Enriched concentrations of soluble salts and metals in these alkaline by-products have the potential to impair plant growth, but such effects were not present at the application rates instituted for tailings and contaminated soil used in this investigation.

It can be hypothesized that the lack of plant water stress during the growth period masked the effects of alkaline by-product metal contaminates in LKD and CKD and soluble salts in CKD. Application rates (dry weight basis) for CKD ranged from 5.3 % to 6.8 % for tailings and

0.9 % to 1.1 % for the contaminated soil (Table 3). As shown in Table 9, both Holnam CKD products did not produce saline soil conditions, i.e. > 4 ds/m, until the application rate exceeded 8 % in Plant Growth Center soil. Ash Grove CKD produced saline conditions in the Plant Growth Center soil when the soil application rate exceeded 4 %. Therefore, it is likely CKD did not produce saline conditions in the contaminated soil, which had a pre-treatment electrical conductivity of 0.6 ds/m. Consequently it was unlikely that lack of a water stress masked out negative impacts of CKD soluble salts on plant growth in the contaminated soil.

Tailings had a pre-treatment electrical conductivity of 9.7 ds/m, but most of these soluble salts were expected to precipitate out of solution when the pH was raised into the 7.0 - 8.4 range. However, the portion of soluble salts that fail to precipitate in concert with those introduced with Ash Grove CKD treatment, and to a lessor degree by Holnam CKD, likely created a saline tailings condition. This increase in tailings soil salinity may have contributed to lower plant biomass measured with Ash Grove CKD. A saline condition in the soil increases the osmotic potential between a soil particle and water, which in turn requires the plant to expend greater energy to uptake this water bound to the soil particle. This energy loss by the plant to uptake water may lead to less biomass production above and below ground.

Soluble metals in LKD and CKD were present at concentrations phytotoxic to plant growth at inherent pH levels of 9.6 to 13.7. Although difficult to predict, thus uncertainty was present (see Section 5.3.6), the alkaline by-product metal solubility (i.e. Al, Ba, B, Cd, Cu, Pb, Mn, Ni, Se, V, Zn) was low and not phytotoxic within the soil matrix at an amended pH of 7.0 to 8.4. Consequently it was unlikely that lack of a water stress during the plant growth period masked out metal phytotoxicity issues in LKD and CKD.

Use of alkaline industrial by-products such as Dicalcium Silicate, CKD and LKD to amend soils carries risk since additional contaminants are being incorporated into the soil. These metal contaminants could cause phytotoxic effects if the soil pH moves outside the range of 7.0 to 8.4 over time. For example, permanence of in-situ treatment of acid soils with an alkaline product carries some long term uncertainties. If the soil eventually undergoes acidification, metal contaminants introduced with the alkaline industrial by-product may become soluble and exacerbate phytotoxicity problems. Alternatively, if amended soil fails to undergo carbonation Reactions [3] through [7] for a very extended period of time (e.g. 8 - 15 months) and soil pH remains elevated in the range 10 - 13, seeding into this soil may subject seedlings to metal toxicity issues as well as the caustic chemistry.

Therefore, the lower cost of alkaline industrial by-products comes with increased risk of causing a phytotoxic response. If this risk can be managed, then these plant growth tests indicate alkaline by-products can be used successfully to amend acid soil systems and produce plant growth the same as- or better than- conventional treatment with a $CaCO_3/CaO$ mixture.

7.0 EFFECT OF INCREASING APPLICATION RATE OF ALKALINE PRODUCT ON PLANT GROWTH

7.1 CONCEPT OF THRESHOLD APPLICATION RATE FOR ALKALINE PRODUCTS

It can be hypothesized that alkaline products have a threshold application rate above which plant growth is significantly impaired. As discussed above in Section 6.0, good plant growth resulted when acidic-metal contaminated tailings and soil were amended with Dicalcium Silicate. Previous reports indicated Dicalcium Silicate successfully increased acid soil pH and precipitated metal contaminants from solution (Dollhopf, et al. 1996; Dollhopf and McDaniel 1997), but plant growth failed in amended acid mine waste materials (Kelly 1997). All these investigations used acidic-metalliferous tailings from the Opportunity impoundment located near Anaconda, Montana. However, tailings material collected by Kelly (1997) required a Dicalcium Silicate application rate of 196 tons/1000 tons of tailings, while the required application rate in this investigation was 42.4 tons/1000 tons of tailings (Table 3). These results indicate that Dicalcium Silicate applied to a soil at a rate of 4.2 % (dry weight basis) enabled good plant growth, but an application rate of 19.6 % resulted in very poor plant growth. This suggests there is a threshold application rate for Dicalcium Silicate below which plant growth is good and above which plant growth will fail.

Daniels et al. (1996) evaluated an industrial lime by-product and reported a threshold application rate for soil above which plant growth was impaired. The concept of a threshold application rate may be especially important for alkaline industrial by-products since they often contain soluble salts and/or metal contaminants that have potential to impair plant growth if present at a high concentration in the root zone. In order to better understand this threshold concept, plant growth was measured as a function of increasing application rates for each alkaline product. The Plant Growth Center soil was used in all pots and the dosage rate of each alkaline product was varied.

7.2 SOIL pH CONTROL DURING THE PLANT GROWTH PERIOD

Addition of alkaline amendments initially raised the Plant Growth Center soil pH into a range of 9.0 to 12.0 which is not suitable for plant growth. Amended soils were treated with CO_2 gas and water for months to expedite carbonation Reactions [3] through [7], discussed above, to produce a soil with a pH suitable for plant growth (7.0 - 8.4).

Unamended Plant Growth Center soil pH before and after the 90 day plant growth period ranged from 7.5 to 7.9 (Table 18).

Plant Growth Center soil **amended** with alkaline products were all in a suitable range (7.0 - 8.4) prior to seeding (Table 18). Following the 90 day plant growth period all treatments had a mean pH in the range 7.1 to 8.4, except for Holnam cement kiln dust (CKD) and Ash Grove

Table 18. Plant Growth Center soil pH[1] prior to seeding and during the plant growth period as a function of increasing application rates of alkaline amendments.

Amendment Type	pH (s.u.) pre-seeding							pH (s.u.) Basin Wildrye 90 days after seeding							pH (s.u.) Redtop 90 days after seeding						
	Amendment Application Rate [2], %							Amendment Application Rate, %							Amendment Application Rate, %						
	0	2	4	6	8	10	12	0	2	4	6	8	10	12	0	2	4	6	8	10	12
Greymont LKD	7.6	8.0	8.0	7.9	8.0	8.2	8.1	7.7	7.9	8.2	7.1	7.1	8.0	8.0	7.5	7.8	8.0	8.1	8.1	8.1	8.1
Tacoma LKD	7.7	7.5	7.9	7.9	8.0	7.9	7.8	7.7	7.6	7.9	8.0	8.2	8.1	8.0	7.8	7.6	8.2	8.0	8.1	7.9	8.2
MT Limestone LKD	7.7	8.0	7.6	7.6	7.7	7.6	7.8	7.7	8.1	8.1	8.1	8.1	8.0	8.1	7.7	8.1	8.0	7.9	7.9	8.0	8.0
Holnam (CH_4) CKD	7.6	7.6	8.2	8.4	7.9	8.2	8.3	7.7	8.1	8.3	8.4	8.4	8.6	8.5	7.5	7.9	8.3	8.4	8.4	8.5	8.4
Holnam (Coal, Coke) CKD	7.6	8.4	8.2	7.9	8.3	8.3	8.3	7.6	8.0	8.3	8.4	8.4	8.2	8.5	7.5	8.1	8.1	8.5	8.4	8.5	8.6
Ash Grove CKD	7.7	7.8	8.0	8.1	8.3	8.2	8.4	7.6	7.8	8.1	8.2	8.4	8.4	8.3	7.8	7.8	8.1	8.3	8.4	8.5	8.5
Dicalcium Silicate	7.7	8.4	8.4	8.3	7.8	7.9	7.9	7.8	7.9	8.1	8.1	8.2	8.2	8.3	7.7	8.1	8.2	8.2	8.3	8.3	8.3
Carbide Lime	7.7	7.6	7.9	8.0	8.1	8.0	8.1	7.9	7.9	7.9	8.0	8.1	8.1	8.2	7.6	8.2	7.9	7.8	8.0	8.1	8.1
$CaCO_3$/CaO	7.6	8.0	8.1	8.2	8.3	8.4	8.4	7.6	8.0	8.1	8.0	8.2	8.3	8.0	7.5	7.8	7.9	8.2	8.4	8.2	8.4

[1] Each pH value in the table is a mean of 5 replications following the 90 day growth period. Prior to seeding, each value in the table is the pH for a single value collected in within a bulk mixing container.

[2] Application rate is on a dry weight basis, i.e. 2 % is equivalent to 20 t amendment/1000 t soil.

CKD. These CKD materials had pH values of 8.5 and 8.6 for soil treated at the 10 % and 12 % application rates. This increase in pH may have been due to sodium hydrolysis [Reaction 8 above] during the plant growth period and resultant formation of sodium hydroxide that will increase the soil solution pH. Both CKD products had a high content of sodium compared to other alkaline products tested.

7.3 EFFECT OF INCREASING ALKALINE AMENDMENT APPLICATION RATES DURING THE INITIAL 14 DAY PLANT GROWTH PERIOD

Percent seed germination, time required for emergence and % survival for Basin Wildrye and Redtop were not significantly different as each alkaline product dosage rate was increased incrementally across the range 0 - 12 % (Tables 19 and 20). The one exception was number of days for Redtop emergence for treatment with Holnam (Coke, Coal) CKD where the 0 % rate required significantly more time compared to the 2 %, 4 %, 6 %, 8 %, and 12 % application rates. Basin Wildrye and Redtop mean shoot height consistently decreased across the 0 % to 12 % dosage range, and these decreases were frequently significant for each alkaline product tested. Therefore, after only a 14 day growth period, plant shoot height was impaired with each 2 % increase in alkaline product dosage increase in the soil matrix across the range 0 % to 12 %. This was the case for all alkaline industrial by-products as well as the $CaCO_3$/CaO mixture.

7.4 EFFECT OF INCREASING ALKALINE AMENDMENT APPLICATION RATES AFTER A 90 DAY PLANT GROWTH PERIOD

Aboveground biomass, plant height, belowground biomass and number of roots at the 5 cm soil depth, all tended to have largest values associated with the 0 % alkaline amendment dosage rate and progressively smaller values with increasing dosage rate up to 12 % (Tables 21 and 22). This loss in plant growth across the 0 - 12 % dosage range was generally significant for aboveground biomass, but not for belowground root biomass. Aboveground biomass for the $CaCO_3$/CaO mixture did not have significant differences across the dosage range, but all alkaline industrial by products had significant differences across the same dosage range. This may indicate enriched metal and soluble salt content in some alkaline by-products cause a more rapid loss in plant growth as dosage rate increases. However, all alkaline products, including the $CaCO_3$/CaO mixture, exhibited the trend where aboveground biomass values decrease with increasing dosage rate in the soil matrix.

7.5 FACTORS CONTRIBUTING TO LOSS IN PLANT GROWTH WITH INCREASING ALKALINE PRODUCT DOSAGE

The loss in plant growth as alkaline product dosage increased is illustrated in Figure 10. Above ground plant biomass when no alkaline product was applied to the Plant Growth Center soil was assigned a relative value of 100 %, indicating optimum plant growth. Means presented in Figure 10 are calculated across data for all 9 alkaline products evaluated and the 5 replications. Incorporation of alkaline products into Plant Growth Center soil at a 2 % application rate (i.e. 20 tons amendment/1000 tons soil) resulted in approximately a 35 % loss in plant biomass. Each

Table 19. Effect of increasing alkaline product application rate on growth of Basin Wildrye 14 days after emergence.

Amendment Dosage, Dry Weight Basis %	Time to Emergence (days)	Germination %	Survival %	Shoot Height (mm)
	Greymont LKD			
0	8.0 a[1]	82.7 a	100.0 a	205.0 a
2	7.4 a	92.0 a	100.0 a	160.5 bc
4	7.8 a	84.0 a	100.0 a	126.9 cd
6	7.8 a	89.3 a	100.0 a	135.2 cd
8	8.0 a	84.0 a	100.0 a	111.7 d
10	7.8 a	97.3 a	100.0 a	95.3 d
12	7.8 a	85.3 a	100.0 a	106.5 d
	Tacoma LKD			
0	7.4 a	89.3 a	100.0 a	174.1 a
2	7.8 a	85.3 a	100.0 a	144.7 a
4	7.8 a	94.7 a	100.0 a	140.9 a
6	7.8 a	94.7 a	100.0 a	143.7 a
8	8.0 a	77.3 a	100.0 a	140.2 a
10	7.8 a	84.0 a	100.0 a	141.7 a
12	7.6 a	89.3 a	100.0 a	132.8 a
	MT Limestone LKD			
0	8.2 a	78.7 a	100.0 a	165.2 a
2	7.4 a	80.0 a	100.0 a	148.9 ab
4	7.6 a	89.3 a	100.0 a	130.8 bc
6	8.0 a	68.0 a	100.0 a	113.6 c
8	7.8 a	82.7 a	100.0 a	104.0.c
10	7.4 a	92.0 a	100.0 a	97.5 c
12	7.8 a	84.0 a	100.0 a	98.5 c
	Holnam (CH_4) CKD			
0	7.8 a	78.7 a	100.0 a	187.9 a
2	7.4 a	82.7 a	100.0 a	153.5 ab
4	8.2 a	86.7 a	100.0 a	165.7 a
6	7.4 a	84.0 a	100.0 a	121.4 bc
8	8.2 a	78.7 a	100.0 a	128.9 bc
10	7.6 a	85.3 a	100.0 a	103.7 c
12	8.2 a	80.0 a	100.0 a	100.0 c
	Holnam (Coal, Coke) CKD			
0	7.2 a	90.7 a	100.0 a	176.7 a
2	7.6 a	89.3 a	100.0 a	140.4 a
4	7.4 a	86.7 a	100.0 a	155.7 a
6	8.0 a	85.3 a	100.0 a	127.3 a
8	7.6 a	88.0 a	100.0 a	140.6 a
10	7.6 a	89.3 a	100.0 a	129.9 a
12	8.0 a	81.3 a	100.0 a	117.3 a
	Ash Grove CKD			
0	7.2 a	89.3 a	100.0 a	177.7 a
2	8.0 a	81.3 a	100.0 a	175.6 a
4	8.0 a	86.7 a	100.0 a	155.1 a
6	8.0 a	82.7 a	100.0 a	113.0 b
8	8.0 a	78.7 a	100.0 a	115.4 b
10	8.4 a	86.7 a	100.0 a	104.6 b
12	8.8 a	64.0 a	100.0 a	92.2 b
	Dicalcium Silicate			
0	7.8 a	94.7 a	100.0 a	158.6 a
2	8.2 a	93.3 a	100.0 a	162.9 a
4	7.8 a	96.0 a	100.0 a	114.8 b
6	8.0 a	76.0 a	100.0 a	97.6 b
8	8.0 a	100.0 a	100.0 a	102.4 b
10	7.4 a	92.0 a	100.0 a	94.5 b
12	7.2 a	92.0 a	100.0 a	106.1 b
	Carbide Lime			
0	7.6 a	96.0 a	100.0 a	183.0 a
2	7.8 a	78.7 a	100.0 a	135.6 abc
4	7.8 a	88.0 a	100.0 a	151.7 ab
6	7.4 a	85.3 a	100.0 a	111.1 bc
8	7.6 a	85.3 a	100.0 a	118.5 bc
10	7.6 a	82.7 a	100.0 a	84.2 c
12	7.8 a	90.7 a	100.0 a	90.7 c
	$CaCO_3$/CaO			
0	7.8 a	93.3 a	100.0 a	180.3 a
2	7.6 a	90.7 a	100.0 a	145.9 ab
4	7.4 a	89.3 a	100.0 a	140.3 ab
6	7.8 a	81.3 a	100.0 a	118.0 b
8	7.6 a	96.0 a	100.0 a	109.1 b
10	7.4 a	86.7 a	100.0 a	96.1 b
12	7.8 a	77.3 a	100.0 a	100.7 b

[1] Means (n = 5)followed by the same letter in the same column are not significantly different (P=0.05).

Table 20. Effect of increasing alkaline product application rate on growth of Redtop 14 days after emergence.

Amendment Dosage, Dry Weight Basis (%)	Time to Emergence (days)	Germination (%)	Survival (%)	Shoot Height (mm)
	Greymont LKD			
0	7.8 a[1]	72.0 a	100.0 a	96.4 a
2	7.0 a	100.0 a	100.0 a	79.5 a
4	7.0 a	100.0 a	100.0 a	77.7 a
6	7.2 a	93.3 a	100.0 a	55.4 ab
8	7.4 a	90.7 a	100.0 a	34.9 b
10	7.4 a	96.0 a	100.0 a	41.7 ab
12	7.6 a	100.0 a	100.0 a	36.3 b
	Tacoma LKD			
0	7.6 a	100.0 a	100.0 a	111.7 a
2	7.0 a	89.3 a	100.0 a	67.4 bc
4	7.4 a	100.0 a	100.0 a	77.8 bc
6	7.2 a	97.3 a	100.0 a	53.9 c
8	7.2 a	100.0 a	100.0 a	49.4 c
10	7.2 a	90.7 a	100.0 a	92.9 ab
12	7.2 a	100.0 a	100.0 a	51.4 c
	MT Limestone LKD			
0	7.2 a	85.3 a	100.0 a	114.6 a
2	7.2 a	80.0 a	100.0 a	52.3 b
4	7.2 a	100.0 a	100.0 a	41.5 b
6	7.0 a	100.0 a	100.0 a	29.6 b
8	7.2 a	96.0 a	100.0 a	42.2 b
10	7.0 a	96.0 a	100.0 a	33.9 b
12	7.6 a	100.0 a	100.0 a	27.3 b
	Holnam (CH$_4$) CKD			
0	8.0 a	84.0 a	100.0 a	95.6 a
2	7.2 a	90.7 a	100.0 a	75.8 ab
4	7.4 a	86.7 a	100.0 a	68.6 ab
6	7.2 a	86.7 a	100.0 a	50.9 bc
8	7.2 a	84.0 a	100.0 a	55.5 bc
10	7.6 a	92.0 a	100.0 a	44.3 bc
12	7.6 a	98.7 a	100.0 a	33.9 c
	Holnam (Coal, Coke) CKD			
0	7.8 a	92.0 a	100.0 a	89.9 a
2	6.8 b	100.0 a	100.0 a	78.0 ab
4	7.2 b	100.0 a	100.0 a	84.2 ab
6	7.0 b	97.3 a	100.0 a	72.4 ab
8	7.0 b	94.7 a	100.0 a	49.3 ab
10	7.4 ab	100.0 a	100.0 a	36.5 b
12	7.0 b	100.0 a	100.0 a	38.1 b
	Ash Grove CKD			
0	7.4 a	93.3 a	100.0 a	91.5 a
2	7.2 a	93.3 a	100.0 a	82.1 ab
4	7.6 a	93.3 a	100.0 a	67.3 abc
6	7.6 a	92.0 a	100.0 a	60.4 bc
8	7.8 a	100.0 a	100.0 a	47.8 c
10	8.2 a	89.3 a	100.0 a	36.5 c
12	8.2 a	100.0 a	100.0 a	39.7 c
	Dicalcium Silicate			
0	7.8 a	85.3 a	100.0 a	109.8 a
2	7.2 a	89.3 a	100.0 a	69.3 b
4	7.4 a	100.0 a	100.0 a	55.4 bc
6	7.4 a	90.7 a	100.0 a	44.9 bc
8	7.6 a	85.3 a	100.0 a	34.4 bc
10	7.0 a	100.0 a	100.0 a	27.3 c
12	7.0 a	100.0 a	100.0 a	33.4 bc
	Carbide Lime			
0	7.8 a	100.0 a	100.0 a	78.7 a
2	7.2 a	89.3 a	100.0 a	70.6 a
4	7.6 a	100.0 a	100.0 a	67.4 a
6	7.2 a	97.3 a	100.0 a	57.3 ab
8	7.6 a	97.3 a	100.0 a	45.2 ab
10	7.4 a	96.0 a	100.0 a	30.7 b
12	7.4 a	100.0 a	100.0 a	44.8 ab
	$CaCO_3$/CaO			
0	8.4 a	92.0 a	100.0 a	78.5 a
2	7.4 a	100.0 a	100.0 a	84.4 a
4	7.8 a	96.0 a	100.0 a	78.3 a
6	7.8 a	92.0 a	100.0 a	68.2 a
8	7.8 a	100.0 a	100.0 a	45.3 b
10	7.4 a	100.0 a	100.0 a	33.3 b
12	7.4 a	100.0 a	100.0 a	39.8 b

[1] Means (n = 5)followed by the same letter in the same column are not significantly different (P=0.05).

Table 21. Effect of increasing alkaline product application rate on Basin Wildrye following a 90 day growth period.

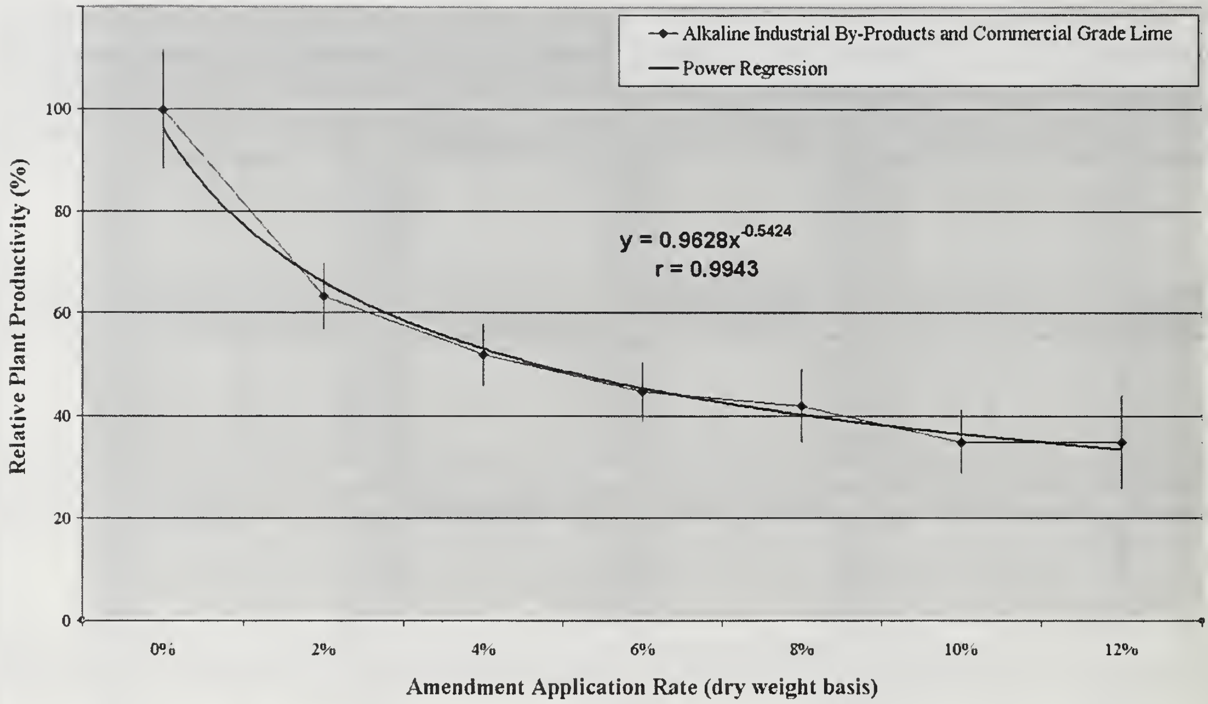
Amendment Dosage, Dry Weight Basis %	Aboveground Height (mm)	Number of Roots 5 cm Depth	Aboveground Biomass (g)	Belowground Biomass (g)
	Greymont LKD			
0	300.6 a[1]	56.0 a	0.504 a	0.460 a
2	271.0 a	41.4 a	0.412 ab	0.431 a
4	215.0 ab	34.2 a	0.299 bc	0.288 a
6	226.2 ab	36.6 a	0.297 bc	0.429 a
8	269.2 a	34.6 a	0.271 bc	0.282 a
10	225.6 ab	34.0 a	0.191 c	0.338 a
12	167.8 b	33.0 a	0.184 c	0.231 a
	Tacoma LKD			
0	312.8 a	43.0 a	0.682 a	0.427 a
2	238.4 a	26.6 a	0.348 b	0.410 a
4	231.6 a	27.8 a	0.301 b	0.357 a
6	222.4 a	18.0 a	0.257 b	0.170 a
8	273.0 a	43.8 a	0.265 b	0.352 a
10	207.4 a	23.6 a	0.259 b	0.248 a
12	256.4 a	31.0 a	0.380 b	0.527 a
	MT Limestone LKD			
0	275.6 a	43.0 a	0.563 a	0.337 a
2	260.6 a	28.0 a	0.354 b	0.344 a
4	232.2 a	21.8 a	0.234 bc	0.371 a
6	211.4 a	42.8 a	0.169 c	0.233 a
8	201.2 a	40.6 a	0.187 c	0.253 a
10	153.4 a	24.8 a	0.114 c	0.207 a
12	161.2 a	22.2 a	0.099 c	0.147 a
	Holnam (CH_4) CKD			
0	290.4 a	42.0 a	0.532 a	0.288 a
2	220.2 a	23.2 a	0.248 b	0.297 a
4	252.2 a	21.6 a	0.287 b	0.282 a
6	239.0 a	38.4 a	0.298 b	0.366 a
8	212.6 a	43.0 a	0.256 b	0.335 a
10	201.2 a	35.4 a	0.155 b	0.208 a
12	184.0 a	28.4 a	0.165 b	0.255 a
	Holnam (Coal, Coke) CKD			
0	311.4 a	31.2 a	0.642 a	0.375 a
2	233.2 a	29.2 a	0.310 abc	0.323 a
4	274.8 a	49.4 a	0.346 ab	0.349 a
6	245.0 a	33.4 a	0.293 abc	0.389 a
8	250.4 a	36.0 a	0.337 abc	0.440 a
10	228.4 a	61.6 a	0.205 c	0.378 a
12	181.6 b	35.6 a	0.157 c	0.290 a
	Ash Grove CKD			
0	270.8 a	54.0 a	0.600 a	0.463 a
2	295.2 a	33.0 a	0.460 ab	0.412 a
4	247.8 abc	46.6 a	0.358 b	0.400 a
6	257.4 ab	21.2 a	0.272 b	0.335 a
8	176.4 c	23.6 a	0.263 b	0.252 a
10	182.8 bc	31.4 a	0.299 b	0.341 a
12	229.4 abc	26.4 a	0.292 b	0.255 a
	Dicalcium Silicate			
0	255.6 a	27.2 a	0.470 a	0.260 a
2	225.4 a	32.0 a	0.274 a	0.276 a
4	204.6 a	38.4 a	0.260 ab	0.183 a
6	195.4 a	28.6 a	0.163 ab	0.203 a
8	208.2 a	29.0 a	0.149 ab	0.214 a
10	171.0 a	32.0 a	0.109 b	0.231 a
12	142.8 a	20.8 a	0.112 b	0.194 a
	Carbide Lime			
0	244.2 a	20.8 a	0.283 a	0.180 a
2	243.6 a	27.2 a	0.301 a	0.262 a
4	220.2 a	30.4 a	0.172 ab	0.190 a
6	211.0 a	25.6 a	0.196 ab	0.273 a
8	148.8 a	28.4 a	0.120 b	0.164 a
10	190.0 a	37.2 a	0.181 ab	0.263 a
12	202.2 a	24.0 a	0.153 ab	0.177 a
	$CaCO_3$/CaO			
0	285.4 a	30.2 a	0.489 a	0.200 a
2	223.0 ab	22.2 a	0.311 b	0.285 a
4	205.6 ab	18.8 a	0.215 bc	0.236 a
6	199.4 ab	32.6 a	0.184 bc	0.271 a
8	162.2 b	42.8 a	0.153 bc	0.287 a
10	162.0 b	28.2 a	0.152 bc	0.240 a
12	132.2 b	27.4 a	0.123 c	0.211 a

[1] Means (n = 5)followed by the same letter in the same column are not significantly different (P=0.05).

Table 22. Effect of increasing alkaline product application rate on growth of Redtop 90 days after emergence.

Amendment Dosage, Dry Weight Basis %	Aboveground Height (mm)	Number of Roots 5 cm Depth	Aboveground Biomass (g)	Belowground Biomass (g)
	Greymont LKD			
0	188.6 ab[1]	25.6 a	0.481 ab	0.147 a
2	202.2 ab	28.2 a	0.278 ab	0.112 a
4	196.4 ab	16.6 a	0.334 ab	0.136 a
6	211.6 a	22.2 a	0.223 ab	0.134 a
8	178.0 ab	17.4 a	0.143 bc	0.137 a
10	158.4 ab	15.4 a	0.174 bc	0.082 a
12	122.6 b	17.0 a	0.063 c	0.065 a
	Tacoma LKD			
0	197.2 a	34.2 a	0.375 a	0.203 a
2	174.8 a	11.4 b	0.311 ab	0.075 ab
4	176.8 a	12.2 b	0.219 ab	0.083 ab
6	136.0 a	23.8 a	0.180 ab	0.151 ab
8	146.8 a	16.8 b	0.128 ab	0.076 ab
10	158.4 a	26.0 a	0.176 ab	0.136 ab
12	135.8 a	15.2 b	0.076 b	0.067 b
	MT Limestone LKD			
0	191.0 a	25.6 a	0.288 a	0.140 a
2	176.4 a	18.0 a	0.304 ab	0.062 a
4	181.6 a	24.6 a	0.156 abc	0.105 a
6	141.2 a	13.6 a	0.105 bcd	0.055 a
8	127.6 a	15.8 a	0.042 d	0.098 a
10	128.8 a	20.2 a	0.071 cd	0.126 a
12	102.6 a	17.8 a	0.028 d	0.049 a
	Holnam (CH_4) CKD			
0	241.4 a	41.8 a	0.541 a	0.237 a
2	170.4 ab	18.4 a	0.199 b	0.104 a
4	169.2 ab	19.6 a	0.156 b	0.131 a
6	151.8 ab	24.0 a	0.139 b	0.124 a
8	144.6 ab	14.0 a	0.122 b	0.098 a
10	158.2 ab	19.6 a	0.101 b	0.102 a
12	124.0 b	24.2 a	0.084 b	0.119 a
	Holnam (Coal, Coke) CKD			
0	194.2 a	22.6 a	0.343 a	0.116 a
2	181.4 a	31.4 a	0.137 b	0.110 a
4	147.0 a	17.8 a	0.116 b	0.105 a
6	170.8 a	21.4 a	0.135 b	0.117 a
8	150.4 a	20.4 a	0.100 b	0.086 a
10	148.4 a	16.4 a	0.084 b	0.060 a
12	130.8 a	12.0 a	0.040 b	0.045 a
	Ash Grove CKD			
0	188.4 a	24.0 a	0.320 a	0.142 a
2	174.0 a	18.8 a	0.335 a	0.124 a
4	175.2 a	23.4 a	0.208 a	0.128 a
6	179.6 a	20.8 a	0.183 ab	0.107 a
8	159.0 a	17.0 a	0.126 ab	0.086 a
10	130.0 a	15.2 a	0.077 b	0.046 a
12	163.2 a	17.8 a	0.082 b	0.083 a
	Dicalcium Silicate			
0	201.0 a	32.2 a	0.414 a	0.172 a
2	170.2 a	20.4 a	0.178 ab	0.061 a
4	180.0 a	14.0 a	0.124 abc	0.099 a
6	151.8 a	22.2 a	0.076 bcd	0.087 a
8	137.0 a	25.0 a	0.056 bcd	0.109 a
10	93.8 a	14.6 a	0.025 d	0.047 a
12	138.4 a	14.8 a	0.047 cd	0.078 a
	Carbide Lime			
0	179.6 a	25.2 a	0.240 a	0.090 a
2	157.8 a	13.0 a	0.188 ab	0.092 a
4	133.8 a	19.4 a	0.092 ab	0.061 a
6	185.0 a	25.6 a	0.093 ab	0.096 a
8	113.2 a	24.0 a	0.049 b	0.122 a
10	128.0 a	31.4 a	0.052 ab	0.114 a
12	117.6 a	15.4 a	0.089 ab	0.058 a
	$CaCO_3$/CaO			
0	163.4 a	22.2 a	0.206 a	0.115 a
2	177.6 a	19.8 a	0.183 a	0.077 a
4	159.0 a	15.0 a	0.200 a	0.047 a
6	150.0 a	24.4 a	0.126 a	0.101 a
8	144.4 a	22.8 a	0.123 a	0.086 a
10	123.2 a	12.6 a	0.058 a	0.048 a
12	129.4 a	24.0 a	0.064 a	0.068 a

[1] Means (n = 5)followed by the same letter in the same column are not significantly different (P=0.05).



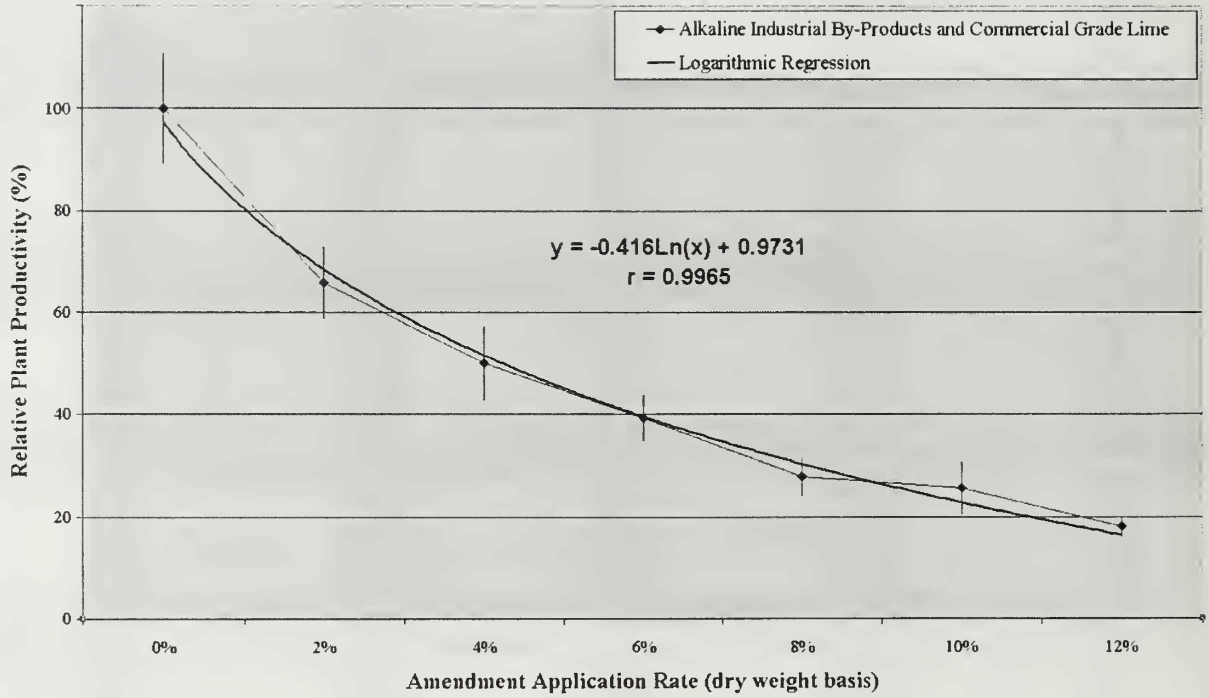


Figure 10. Loss in above ground biomass, Basin Wildrye (top) and Redtop (bottom), with increasing dosage of alkaline amendments. Each point is a mean of 45 observations and the bar on each mean is plus or minus one standard deviation.

subsequent alkaline product application rate increase, i.e. 2 %, 4 %, 6 %, 8 %, 10 % and12 %, produced incrementally less plant biomass. At a 12 % application rate, Basin Wildrye biomass decreased approximately 65 % and Redtop decreased approximately 88 %. All alkaline amendments tested, i.e. the $CaCO_3/CaO$ mixture, CKD and LKD materials, Dicalcium Silicate and Carbide Lime, had a similar result as indicated by the relatively narrow standard deviation bar on each mean in Figure 10. These results help explain plant growth failure with Dicalcium Silicate when the tailings application rate was 19.6 % (Kelly 1997) and good plant growth attained in this investigation with a 4.2 % application rate (Section 6.0 above). Apparently, the greater the excess of alkaline amendment residing in the soil matrix to address future potential acidity issues, the greater will be the loss in plant growth.

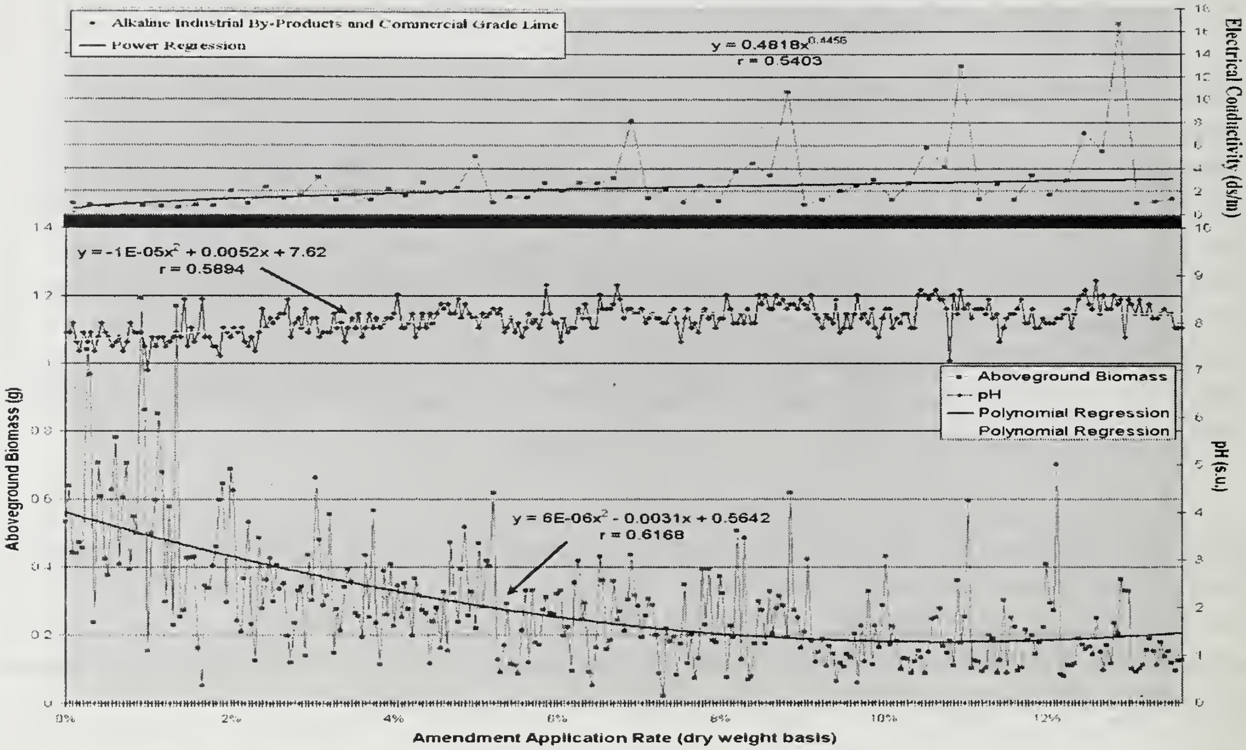
The progressive loss in plant biomass with increasing alkaline product application rate, illustrated in Figure 10, is not consistent with the threshold concept. A typical threshold would be expressed by similar plant biomass values with increasing alkaline product application, followed by an abrupt decline in plant biomass at the threshold application rate. **The principle presented in Figure 10 is that for each alkaline product, the greater the application rate the less will be the plant growth, i.e. no threshold dosage was present.**

However, these results should not be immediately interpreted to mean high application rates will result in plant growth failure for all alkaline products. Consider Tacoma LKD which was applied at a high rate of 11.6 % (116.6 tons/1000 tons tailings) to both tailings and the Plant Growth Center soil in the experiment discussed in Section 6.0 above. This application rate facilitated good above ground plant growth in tailings while growth in the Plant Growth Center soil was on the average 350 % greater. Clearly, the 11.6 % application rate is below a threshold value where plant growth fails, but results presented in Figure 10 indicate if a lower application rate could have been applied, more plant biomass would have been produced.

Therefore, when designing the alkaline amendment application rate for a project landscape, procedures should be used to apply the correct amount of alkaline material as opposed to an known excess. Excess applications emanate from insufficient data to account for variability across the landscape, thus more alkaline product is applied than required to insure the high rate captures this variability and soil acidification does not reappear in the future. Minimizing error of over application of alkaline material will increase plant growth and decrease treatment cost.

7.5.1 Correlation of Soil pH and Electrical Conductivity to Increasing Amendment Application Rate and Loss of Plant Growth

Loss in plant growth with increasing alkaline amendment dosage in relation to soil pH and electrical conductivity is shown in Figure 11. Loss in aboveground plant biomass was significantly correlated ® = 0.62 and 0.56) to increased amendment application rate. Increased soil pH associated with greater amendment application rates was significantly correlated ® = 0.59 and 0.54) to loss in above ground plant biomass. The pH increased from approximately 7.7 to 8.3 across the alkaline amendment application rate range of 0 % to 12 %. Similarly, increased



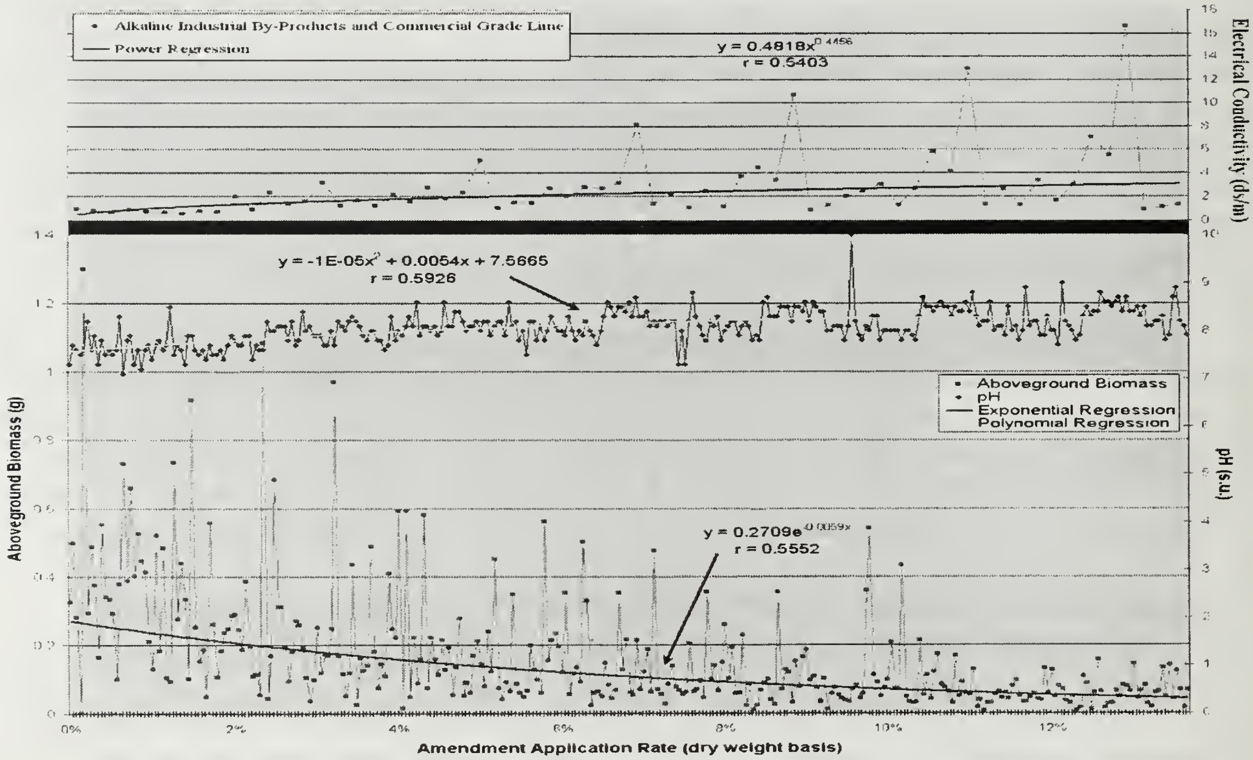


Figure 11. Loss in above ground biomass, Basin Wildrye (top) and Redtop (bottom), in relation to increased soil pH, electrical conductivity and alkaline amendment application rate.

soil electrical conductivity associated with greater amendment application rates was significantly correlated ® = 0.54) to loss in aboveground plant biomass. On the average, the soil electrical conductivity increased from approximately 0.8 ds/m to 4.5 ds/m across the alkaline amendment application rate range of 0 % to 12 %. These results suggest that elevated soil pH and soluble salts associated with increasing alkaline amendment application rates contributed to a loss in plant biomass. The mechanisms causing loss in plant growth may be i) lower availability of nitrogen, phosphorus, and potassium (see Figure 7) as pH increases, and ii) greater expenditure of energy by the plant root to uptake water due to a soluble salt induced increase in the osmotic potential between soil and water.

As shown in Tables 23 and 24, pH in the amended soil frequently increased significantly as the alkaline product application rate increased across the range of 0 % to 12 %. The equilibrium pH for a soil solution saturated with $CaCO_3$ is approximately 8.3. Therefore, pH values greater than 8.3 may have been caused by either i) applied CaO or $Ca(OH)_2$ that failed to carbonate during the "mellowing" time period or ii) NaOH produced from the hydrolysis of excess sodium emanating from the applied alkaline product, especially CKD. Increased soil pH with increasing alkaline product application rate may have been a contributing factor to loss in plant biomass.

Linear correlation coefficients between soil pH and aboveground plant biomass for each alkaline product are presented in Table 25. Nearly all regressions were significant at the 10 % probability level and many were significant at the 5 % level ($P < 0.05$). These results indicate loss in plant biomass was correlated to increases in soil pH which were attributable to increasing alkaline amendment dosage (0 % to 12 %). Note the correlation coefficient squared (i.e. r^2) is the coefficient of determination which indicates the amount of the problem explained by the regression analysis. Most significant coefficient of determination values were well below 0.5

Table 23. Soil pH following a 90 day plant growth period for Basin Wildrye as a function of different alkaline amendments and application rates.

Amendment Type	Amendment Application Rate [1]						
	0 %	2 %	4 %	6 %	8 %	10 %	12 %
Greymont LKD	7.7 a[2]	7.8 ab	8.2 b	8.1 b	8.1 b	8.0 b	8.0 b
Tacoma LKD	7.7 a	7.6 a	7.9 b	8.0 b	8.2 b	8.1 b	8.0 b
MT Limestone LKD	7.7 a	8.1 b	8.1 b	8.1 b	8.1 b	8.0 b	8.1 b
Holnam (CH_4) CKD	7.7 a	8.1 b	8.3 bc	8.3 bc	8.4 c	8.6 c	8.5 c
Holnam (Coal, Coke) CKD	7.6 a	8.1 b	8.3 b	8.4 b	8.4 b	8.2 b	8.5 b
Ash Grove CKD	7.6 a	7.8 b	8.1 c	8.2 c	8.3 c	8.4 c	8.3 c
Dicalcium Silicate	7.8 a	7.9 a	8.1 a	8.1 a	8.2 a	8.2 a	8.3 a
Carbide Lime	7.9 a	8.0 a	7.9 a	8.0 a	8.1 a	8.1 a	8.2 a
$CaCO_3$/CaO	7.6 a	8.0 b	8.1 b	8.0 b	8.2 b	8.3 b	8.0 b

[1] Application rate is on a dry weight basis, i.e. 2 % is equivalent to 20 t amendment/1000 t soil.
[2] Means (n = 5) followed by the same letter in the same row are not significantly different (P = 0.05).

Table 24. Soil pH following a 90 day plant growth period for Redtop as a function of different alkaline amendments and application rates.

Amendment Type	Amendment Application Rate [1]						
	0 %	2 %	4 %	6 %	8 %	10 %	12 %
Greymont LKD	7.5 a[2]	7.8 b	8.0 b	8.1 b	8.1 b	8.1 b	8.1 b
Tacoma LKD	7.8 ab	7.6 a	8.2 c	8.0 bc	8.1 c	8.0 bc	8.2 c
MT Limestone LKD	7.7 a	8.1 b	8.0 b	8.0 b	8.0 b	8.0 b	8.0 b
Holnam (CH_4) CKD	7.5 a	7.9 b	8.3 c	8.4 c	8.4 c	8.5 c	8.4 c
Holnam (Coal, Coke) CKD	7.5 a	8.1 b	8.1 b	8.5 c	8.4 c	8.5 c	8.6 d
Ash Grove CKD	7.8 a	7.8 a	8.1 b	8.3 b	8.4 b	8.5 b	8.5 b
Dicalcium Silicate	7.7 a	8.1 b	8.2 b	8.2 b	8.3 b	8.3 b	8.3 b
Carbide Lime	7.6 a	8.0 b	7.9 b	7.8 ab	8.0 b	8.1 b	8.1 b
$CaCO_3$/CaO	7.5 a	7.8 ab	8.0 bc	8.2 c	8.4 c	8.2 c	8.4 c

[1] Application rate is on a dry weight basis, i.e. 2 % is equivalent to 20 t amendment/1000 t soil.
[2] Means (n = 5) followed by the same letter in the same row are not significantly different (P =0.05).

Table 25. Linear correlation coefficient (r) between above ground plant production and soil pH at time of harvest.

Amendment Type	Basin Wildrye		Redtop	
	r [1]	P value [2]	r [1]	P value [2]
Greymont LKD	0.38	0.02*	0.23	0.18
Tacoma LKD	0.17	0.32	0.22	0.21
MT Limestone LKD	0.59	<0.01*	0.14	0.42
Holnam (CH_4) CKD	0.65	<0.01*	0.52	<0.01*
Holnam (Coal, Coke) CKD	0.07	0.70	0.62	<0.01*
Ash Grove CKD	0.53	<0.01*	0.56	<0.01*
Dicalcium Silicate	0.55	<0.01*	0.40	0.02*
Carbide Lime	0.25	0.10	0.12	0.50
$CaCO_3$/CaO	0.58	<0.01*	0.40	<0.01*

[1] Correlation coefficient (r) based on regression of 35 values, i.e. 5 replications x 7 amendment application rates.
[2] Linear correlation is significant (*) at P < 0.05.

indicating increases in soil pH with increased amendment dosage was only a part of the reason a loss in plant growth was measured. Other factors besides soil pH contributed to the loss in plant growth.

Linear correlation coefficients between soil electrical conductivity (EC) and aboveground plant biomass for each alkaline product are presented in Table 26. Nearly half of these

Table 26. Linear correlation coefficients (r) between above ground plant production and soil electrical conductivity at the time of harvest.

Amendment Type	Basin Wildrye		Redtop	
	r [1]	P value [2]	r [1]	P value [2]
Greymont LKD	0.74[1]	0.06	0.93	0.01*
Tacoma LKD	0.22	0.64	0.44	0.32
MT Limestone LKD	0.91	<0.01*	0.79	0.03*
Holnam (CH_4) CKD	0.73	0.06	0.70	0.08
Holnam (Coal, Coke) CKD	0.55	0.20	0.87	<0.01*
Ash Grove CKD	0.43	0.34	0.86	<0.01*
Dicalcium Silicate	0.35	0.44	0.61	0.14
Carbide Lime	0.32	0.49	0.44	0.32
$CaCO_3$/CaO	0.67	0.10	0.06	0.91

[1] Correlation coefficient (r) based on regression of 7 values, i.e. 1 replication x 7 amendment application rates.
[2] Linear correlation is significant (*) at P < 0.05.

regressions were significant at the 10 % probability level and a few were significant at the 5 % level ($P < 0.05$). These results indicate loss in plant biomass was correlated to increases in soil EC which were attributable to increasing alkaline amendment dosage for some alkaline products. The coefficient of determination (r^2) for significant regressions were relatively high indicating EC was a key factor contributing to loss in plant biomass as the amendment dosage rate was increased.

In summary, linear correlation analysis indicated increasing soil pH and electrical conductivity as alkaline amendment dosage rate increased contributed to loss in above ground plant biomass. Loss in plant growth with increasing amendment dosage was due to other unidentified factors, which are presumed to be associated with alkaline amendment physicochemical characteristics.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Plant growth was evaluated in acidic-metalliferous tailings and acidic-metal contaminated soil after being neutralized with three lime kiln dust (LKD) industrial by-products, three cement kiln dust (CKD) industrial by-products, industrial by-products Dicalcium Silicate and Carbide Lime, and a lime product mixture of $CaCO_3$ / CaO. In addition, effects of increasing alkaline product dosage from 0 % to 12 % (soil dry weight basis) on plant growth were investigated. Replicated plant growth tests were conducted in greenhouse facilities under ideal environmental conditions.

8.1 ALKALINE INDUSTRIAL BY-PRODUCT COMPOSITION

- Most alkaline by-products investigated were composed of a fine particle size (<60 mesh) needed to facilitate neutralization reactions in acid soil systems. High coarse fragment content (>60 mesh) in a few by-products, as much as 55 % (weight basis), will likely impact the cost feasibility of their use on large projects.

- The calcium carbonate equivalence of alkaline by-products ranged from modest (69 %) to high (127 %) and each contained the compounds $CaCO_3$, CaO and $Ca(OH)_2$ in an amount suitable for attaining precipitation of metals in an acidic soil system.

8.2 ALKALINE BY-PRODUCT SALT AND METAL CONTENT

- All CKD materials were both saline (66.8 - 97.3 ds/m) and sodic (SAR 28.5 - 40.1). All LKD materials, Dicalcium Silicate and Carbide Lime were neither saline nor sodic.

- Soluble salt in CKD made a soil saline (>4 ds/m) with application rates as low as 4 % (soil dry weight basis).

- Metal enrichment in industrial by-products was as follows:

  - total vanadium in CKD and LKD;
  - total and water soluble aluminum in most by-products;
  - total barium in most CKD and LKD;
  - total and water soluble boron in some by-products;
  - water soluble selenium in CKD;
  - total zinc and water soluble zinc in LKD and CKD; and
  - total arsenic, cadmium, chromium, copper, lead, manganese, and nickle in LKD and CKD.

Metals were often present at phytotoxic concentrations in the alkaline by-product matrix which had a pH that ranged from 9.9 to 13.7. However, evidence indicted phytotoxic concentrations may have been mitigated I) when diluted in the soil profile at a typical application rate of 2 % to 10 % (soil dry weight basis), and ii) by an amended soil pH in the range of 7.0 - 8.4 when these metal contaminants were present at low concentrations in the soil solution.

- Treatment design risk is increased when alkaline industrial by-products are used to amend soils. Meaning additional metal contaminants are being incorporated into the root zone and these contaminants may cause phytotoxic effects in the future if the soil pH migrates outside the 7.0 - 8.4 boundary condition in the future.

8.3 ALKALINE BY-PRODUCT EFFECTS ON PLANT GROWTH

- When tailings (pH 1.8) was not amended with an alkaline amendment, the result was no plant growth. When the contaminated soil (pH 5.0) was not amended, mean plant biomass was comparatively very small.

- All alkaline products produced a desired soil pH (7.0 - 8.4) in the root zone during plant growth tests.

- Following a 111 day plant growth period for Basin Wildrye and Redtop all alkaline industrial by-products tested had plant growth equal to-or greater than-the $CaCO_3$/CaO mixture. This was the case in tailings and the contaminated soil for above ground plant biomass, plant height, root biomass, root depth, and number of roots at the 5 cm and 10 cm soil depths.

- A ranking procedure indicated soil treatment with Tacoma LKD produced the most above and below ground biomass followed closely by treatment with Dicalcium Silicate. Greymont LKD, MT Limestone LKD, and both Holnam CKD products each produced good above and below ground plant biomass, but somewhat less than with Tacoma LKD and Dicalcium Silicate. Treatment with the $CaCO_3$/CaO mixture, Ash Grove CKD, and Carbide Lime produced the least plant biomass and were ranked the lowest among the alkaline products tested.

- Based on data from this investigation, it is **recommended** that Federal and State agencies permit the use of alkaline industrial by-products discussed in this report for in-situ soil remediation projects. All parties involved must recognize the potential lower cost of alkaline by-products comes with the risk that additional metals will be introduced into the soil that may in the future cause phytotoxic effects if the soil pH migrates outside the 7.0 - 8.4 boundary condition.

- It is **recommended** that new alkaline products, or products studied in this investigation that are being manufactured in a significantly different manner such as fuel type, be chemically analyzed for metals and soluble salts similar to the protocol used in this study. If uncertainty results from this analysis regarding suitability for plant growth, controlled plant growth tests should be completed prior to approval for use in soil remediation.

- For any alkaline product, including the $CaCO_3$/CaO mixture, the greater the application rate the less will be the plant growth. Starting with an ideal soil matrix for plant growth, each 2 % increase in the alkaline amendment application rate caused an incremental decrease in above ground plant biomass. Over the amendment application range of 0 % to 12 % the loss in plant biomass was 65 % for Basin Wildrye and 88 % for Redtop. The greater the excess of alkaline amendment residing in the soil matrix needed to address future potential acidity issues, the greater will be the loss in plant growth.

- Loss in plant biomass as alkaline product dosage rate increased across the range of 0 % to 12 % was correlated to increases in soil pH and electrical conductivity.

- It is **recommended** that when designing the alkaline amendment application rate for a project landscape, procedures should be used to apply the correct amount of alkaline material as opposed to an known excess. Excess applications emanate from insufficient data to account for variability across the landscape, thus more alkaline product is applied than required to insure the high rate captures this variability and soil acidification does not reappear in the future.

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APPENDIX A

DATA QA/QC STATEMENT

Contract Laboratory Analyses

Several separate sample batches associated with this project were submitted for laboratory analyses by Energy Laboratories, Billings, MT. With one minor exception, all laboratory QA/QC parameters were within control limits and there is no associated limits (data flags) to the use of the resulting data. Sample batches are summarized below.

Batch 00-57442 -1-11 (11 samples). This batch was submitted September 01, 2000 for saturated paste analyses for Ca, Mg, Na, Al, As, B, Cd, Cu, Fe, Pb, Mn, Se, Zn, SO_4, and Cl; and for sulphur fractionation acid base account (ABA) for 3 of the 11 samples. One field duplicate (DS-001, duplicate of SR-001) was included in this batch. All laboratory quality control samples (duplicates, spikes, and blanks) associated with this batch were within control limits except for Na (used to determine SAR). The RPD for Na analysis of OP-001 was 33 percent. Although the Na concentration in this sample was low (3.2 mg/l), it was above 5 times the detection limit. The resulting calculated SAR values were 0.02 and 0.03 for the duplicate and natural sample respectively. The usability of the SAR data should not be affected. Laboratory spike recoveries ranged from 90 to 102 percent and duplicate relative percent differences (RPD) ranged from 0 to 8.7 percent except for Na as noted above.

Batch 00-57442 -1 (total of 13 samples). This batch was analyzed for total analyses of Al, As, Ba, Be, B, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Hg, Ni, K, Se, Ag, Sn, P, V, and Zn. Three samples were analyzed for only Al, As, Cu, Pb, Mn, and Zn while additional TCLP analyses for As, Ba, Cd, Cr, Pb, Hg, Se, and Ag were performed for 9 of the samples. All laboratory QA/QC parameters associated with these samples were within control limits. Maximum RPD for the field duplicate (DS-001) was 7.7 percent.

- Batch 00-58053-1-2 (2 samples). This batch was submitted September 19, 2000 for saturated paste analyses for Ca, Mg, Na, Al, As, B, Cd, Cu, Fe, Pb, Mn, Se, Zn, SO_4, Cl, and lime as $CaCO_3$. All laboratory QA/QC parameters associated with these samples were within control limits. No field QA/QC samples submitted with these two samples.

- Batch 01-56507 (5 samples). These samples were submitted August 01, 2001 for saturated paste analyses of aluminum and vanadium. All laboratory QA/QC parameters associated with these samples were within control limits. No applicable field QA/QC samples submitted with these samples.

- Batch 01-56735 (D-02, G-02). These samples were submitted August 07, 2001 for total analyses of aluminum and vanadium respectively. All laboratory QA/QC parameters

associated with these samples were within control limits. No field QA/QC samples submitted with these two samples.

- Batch 00-59133 (3 samples). These kiln dust samples were submitted for analysis of calcium carbonate equivalence (lab report dated November 2, 2000). All laboratory QA/QC parameters associated with these samples were within control limits. No field QA/QC samples submitted with these samples.

Soil Electrical Conductivity And pH Measurements At MSU

Electrical conductivity and pH (both Fisher glass and Scientific Instruments stainless steel electrodes) measurements were made for substrates used to grow plants during this investigation. These measurements were made utilizing 3 point (pH 4, 7, and 10) calibrations for the Fisher glass electrode, and 2 point (either pH 4, 7 or pH 7, 10) calibrations for the Scientific Instruments stainless steel electrode, and a continuing calibration check for each batch of 20 natural samples. The meter was recalibrated if off more than 0.1 standard units (SU).

Relative percent difference (RPD) was determined for pH using sample splits of the contaminated soil collected from Stucky Ridge, Anaconda, MT. The RPD for pH using the Fisher glass electrode was 1.29 %. Standard reference material (SRM) was obtained from the Reclamation Research Laboratory, Montana State University, in order to evaluate accuracy of pH measurements. Recovery tests for SRM ranged from 97 % to 99 %. Using this SRM, the relative percent difference for soil pH was 0.26 % for the Scientific Instruments stainless steel electrode, and ranged from 0.37 % to 0.50 % for the Fisher glass electrode.

Electrical conductivity (EC) measurements were also made utilizing 3 point calibrations. Linear regression of conductivity bridge output and standard values were used to determine actual sample values. Standard reference material (SRM) was obtained from the Reclamation Research Laboratory, Montana State University, in order to evaluate accuracy of EC measurements. The difference between the established SRM value (3.3 ds/m) and the measurement (3.16) was 0.14 ds/m. The RPD for samples SR-001 and DS-001 was 18 %.

Analyses of EC in soils amended with alkaline products included 3 field duplicate samples. These were treatments identified as Ash Grove CKD 12 %, Holnam (CH_4) CKD 2 %, and MT Limestone LKD 2 %. The RPD for these samples were 24.1 %, 35.3 %, and 19.4 % percent, respectively.

APPENDIX B

Data Collections for Plant Growth Measurements

Table 27. Number of days required for emergence in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	5	6	5	7	5	6	5	6	5	5	5	6	5	5	5	5	5	6	ND	ND
Contaminated Soil	5	8	5	5	5	6	5	6	6	5	5	7	5	5	5	7	5	6	8	5
PGC Soil	5	6	5	6	5	5	5	6	5	7	5	6	5	5	5	6	5	5	5	6
Replication 2																				
Tailings	6	6	5	6	6	10	5	6	5	7	5	6	5	6	5	7	5	6	ND	ND
Contaminated Soil	5	7	5	6	5	5	5	6	5	7	5	6	5	5	5	5	7	6	9	7
PGC Soil	5	6	5	7	5	6	5	7	5	5	5	5	5	7	5	6	5	6	5	5
Replication 3																				
Tailings	7	8	6	6	6	6	5	6	5	6	6	5	5	7	6	8	5	6	ND	ND
Contaminated Soil	5	5	5	6	5	6	5	5	7	5	5	6	5	6	5	5	5	5	7	7
PGC Soil	5	5	5	5	5	5	5	7	5	5	5	5	5	8	5	5	5	5	5	5
Replication 4																				
Tailings	6	9	8	7	8	7	8	8	7	8	6	9	7	6	5	6	7	8	ND	ND
Contaminated Soil	6	6	6	7	6	8	7	8	7	7	7	8	6	7	7	7	6	6	ND	7
PGC Soil	5	6	5	7	5	6	5	7	7	5	8	9	6	7	6	5	5	5	6	5
Replication 5																				
Tailings	7	6	9	8	6	7	6	7	6	7	7	7	6	7	6	7	5	6	ND	ND
Contaminated Soil	6	6	6	6	6	7	8	7	7	8	7	6	6	7	7	7	6	5	8	8
PGC Soil	6	6	6	6	6	6	5	5	9	6	5	6	5	6	5	6	5	7	5	5
Replication 6																				
Tailings	7	8	7	8	7	7	7	7	7	9	8	7	5	7	6	7	6	6	ND	ND
Contaminated Soil	6	7	6	7	6	7	5	7	6	7	6	7	6	7	6	7	5	2	ND	7
PGC Soil	5	6	5	7	6	8	5	6	5	6	5	7	5	7	6	5	5	6	5	5
Replication 7																				
Tailings	6	7	7	7	7	7	6	5	6	6	7	7	6	7	6	7	6	6	ND	ND
Contaminated Soil	7	6	7	7	6	6	6	7	6	6	5	7	6	7	6	7	7	7	ND	7
PGC Soil	6	6	6	7	6	7	6	7	6	7	6	7	6	7	6	7	7	6	6	5
Replication 8																				
Tailings	6	7	6	8	6	7	8	7	6	8	7	17	6	7	7	8	7	7	ND	ND
Contaminated Soil	7	8	6	7	7	7	7	7	7	7	7	6	7	7	8	8	7	8	10	10
PGC Soil	7	6	7	8	8	8	7	8	7	7	8	8	8	8	7	6	7	7	7	7

ND = No Data

Table 28. Germination (number of seedlings emerged/15 seeds, 14 day post-emergence) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	15	11	15	10	15	9	15	12	15	13	15	14	15	13	15	12	15	9	0	0
Contaminated Soil	15	4	15	10	15	11	15	11	1	14	15	12	15	9	15	1	15	8	7	7
PGC Soil	15	13	15	12	13	10	14	7	15	9	9	13	15	14	8	11	12	9	15	14
Replication 2																				
Tailings	15	12	15	11	15	4	15	12	15	2	15	11	15	9	15	12	15	8	0	0
Contaminated Soil	15	8	15	8	15	11	15	12	15	6	15	9	15	9	9	3	6	9	3	6
PGC Soil	15	12	15	14	15	11	15	13	15	13	8	11	15	8	14	11	15	12	15	15
Replication 3																				
Tailings	15	13	15	11	15	13	15	14	15	14	11	11	15	2	12	10	6	15	0	0
Contaminated Soil	15	11	15	9	15	13	15	11	15	12	15	9	14	12	15	11	15	6	1	11
PGC Soil	15	13	14	11	10	8	9	11	12	12	11	5	15	2	15	15	15	13	15	13
Replication 4																				
Tailings	11	12	12	13	11	11	6	11	8	13	15	11	9	12	15	14	15	10	0	0
Contaminated Soil	10	12	15	12	7	10	15	10	12	10	7	11	15	10	7	14	15	3	0	10
PGC Soil	15	12	9	9	15	11	15	12	13	11	11	3	15	6	15	13	15	8	15	13
Replication 5																				
Tailings	9	13	10	12	15	12	15	8	15	11	15	10	15	10	11	15	15	15	0	0
Contaminated Soil	10	13	6	12	15	11	10	13	8	13	13	12	15	9	15	12	15	8	3	11
PGC Soil	15	12	15	11	15	15	11	14	13	12	15	15	13	11	15	13	15	11	15	14
Replication 6																				
Tailings	15	7	15	8	15	9	15	12	15	5	10	13	15	8	15	15	15	10	0	0
Contaminated Soil	15	14	15	15	15	6	15	11	15	11	15	10	15	10	15	13	15	15	0	13
PGC Soil	15	15	15	13	15	6	15	13	15	15	15	15	15	15	15	15	15	15	15	14
Replication 7																				
Tailings	15	12	10	9	13	9	15	15	15	12	15	10	15	14	15	13	15	13	0	0
Contaminated Soil	8	14	12	13	15	12	12	8	11	13	15	5	12	12	15	8	15	7	0	7
PGC Soil	11	15	15	15	15	12	15	14	15	15	15	11	15	15	15	13	15	9	15	11
Replication 8																				
Tailings	15	8	15	12	15	12	15	11	15	7	15	10	15	11	12	9	15	11	0	0
Contaminated Soil	15	9	15	13	15	8	15	14	15	10	15	11	12	11	9	9	13	13	1	13
PGC Soil	15	15	15	11	3	10	15	8	15	12	9	11	11	14	12	15	15	12	15	11

Table 29. Survival (number of seedlings survived/emerged, 14 day post-emergence) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	15	11	15	10	15	9	15	12	15	13	15	14	15	13	15	12	15	9	ND	ND
Contaminated Soil	15	4	15	10	15	11	15	11	1	14	15	12	15	9	15	1	15	8	7	7
PGC Soil	15	13	15	12	13	10	14	7	15	9	9	13	15	14	8	11	12	9	15	14
Replication 2																				
Tailings	15	12	15	11	15	4	15	12	15	2	15	11	15	9	15	12	15	8	ND	ND
Contaminated Soil	15	8	15	8	15	11	15	12	15	6	15	9	15	9	9	3	6	9	3	6
PGC Soil	15	12	15	14	15	11	15	13	15	13	8	11	15	8	14	11	15	12	15	15
Replication 3																				
Tailings	15	13	15	11	15	13	15	14	15	14	11	11	15	2	12	10	6	15	ND	ND
Contaminated Soil	15	11	15	9	15	13	15	11	15	12	15	9	14	12	15	11	15	6	1	11
PGC Soil	15	13	14	11	10	8	9	11	12	12	11	5	15	2	15	15	15	13	15	13
Replication 4																				
Tailings	11	12	12	13	11	11	6	11	8	13	15	11	9	12	15	14	15	10	ND	ND
Contaminated Soil	10	12	15	12	7	10	15	10	12	10	7	11	15	10	7	14	15	3	ND	10
PGC Soil	15	12	9	9	15	11	15	12	13	11	11	3	15	6	15	13	15	8	15	13
Replication 5																				
Tailings	9	13	10	12	15	12	15	8	15	11	15	10	15	10	11	15	15	15	ND	ND
Contaminated Soil	10	13	6	12	15	11	10	13	8	13	13	12	15	9	15	12	15	8	3	11
PGC Soil	15	12	15	11	15	15	11	14	13	12	15	15	13	11	15	13	15	11	15	14
Replication 6																				
Tailings	15	7	15	8	15	9	15	12	15	5	10	13	15	8	15	15	15	10	ND	ND
Contaminated Soil	15	14	15	15	15	6	15	11	15	11	15	10	15	10	15	13	15	15	ND	13
PGC Soil	15	15	15	13	15	6	15	13	15	15	15	15	15	15	15	15	15	15	15	14
Replication 7																				
Tailings	15	12	10	9	13	9	15	15	15	12	15	10	15	14	15	13	15	13	ND	ND
Contaminated Soil	8	14	12	13	15	12	12	8	11	13	15	5	12	12	15	8	15	7	ND	7
PGC Soil	11	15	15	15	15	12	15	14	15	15	15	11	15	15	15	13	15	9	15	11
Replication 8																				
Tailings	15	8	15	12	15	12	15	11	15	7	15	10	15	11	12	9	15	11	ND	ND
Contaminated Soil	15	9	15	13	15	8	15	14	15	10	15	11	12	11	9	9	13	13	1	13
PGC Soil	15	15	15	11	3	10	15	8	15	12	9	11	11	14	12	15	15	12	15	11

ND = No Data

Table 30. Shoot Height (height from soil to longest leaf (mm), 14 day post-emergence) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	32	100	37	104.3	20.2	101	18.3	107.4	27.1	108.7	22	110	25	120	27.3	111.2	26.8	118.2	ND	ND
Contaminated Soil	30	70	40	105.6	37.1	105	35.1	96.6	42	124.8	32.1	75	38.5	96	25	130	33	129.5	9	29.4
PGC Soil	32.6	122.3	46.4	146.2	30.8	120.6	32	114.2	29	126.3	55	117.6	42	130	37.1	142.7	40.2	135	57.1	116
Replication 2																				
Tailings	23	101	25.3	105	13	38	15.8	98	31	99.5	19.2	90	15.2	90	23	92.5	30.1	63.7	ND	ND
Contaminated Soil	30	92.3	37	92	36.6	101.2	30.6	125.2	35	94.5	28	101	37	115	30	115	18	120	8	40.3
PGC Soil	37.1	107.1	49	145.8	35.1	105.2	46.2	116.3	37	105	40	125	45	99.8	32	112.3	56.2	146.1	49.6	139.2
Replication 3																				
Tailings	25	68.2	28.3	97	19.6	70	27.5	86	31	100	17.5	91.6	27	57.5	16	67.2	18	99	ND	ND
Contaminated Soil	27	105	35	96	31.2	92	25	107	27.5	115	32	97	30	105.2	33	92.4	30	110	10	40.8
PGC Soil	37	113.2	41	92.3	25	80	56.6	125	33	88.4	45	70.6	45.2	91	35.2	120.2	52	126	60.2	110.5
Replication 4																				
Tailings	30	93	17	95	22	68.5	24.2	120.5	21.8	99.5	21.5	82.5	23.5	87.5	18	97.8	26.3	63.7	ND	ND
Contaminated Soil	33	100	43.3	80	26.6	128.7	30.5	111.2	20	88.8	91	104.7	29	118.8	46	105.5	31.7	126	ND	47.3
PGC Soil	35	120	58	123.3	35	102	37	93.8	19.5	85	53.7	73.6	43.6	81.5	43.7	101.3	64	115	59.5	112.6
Replication 5																				
Tailings	13.8	97.5	13	78.7	27.5	75	27	96.3	30	92	22.8	72.5	33.5	88.8	28.6	82.5	23	115	ND	ND
Contaminated Soil	36.6	118.3	24.3	94.2	26.2	113.8	23	91.3	19.8	111.2		97.5	34	122.5	26.3	95	21.7	86.6	9	43.7
PGC Soil	45	92.5	62	110	29.2	111.2	45.3	117	25	106.4	48.8	123.3	34.1	113.7	36.3	119.7	65	107.5	65	115
Replication 6																				
Tailings	18.2	82	31	103.2	18.5	96	26	115.5	18.2	109	15	91.6	31	82.2	28.3	82.5	30	97.3	ND	ND
Contaminated Soil	29.2	98	26	117.5	26.2	98.7	26.4	108.7	29	117.5	28	98.5	33	111.2	35.2	128	35.2	81.3	ND	28.7
PGC Soil	45	105	50	126.7	28.3	99.5	32	115.1	31.3	97	45.1	122.5	35	116.2	36	98.6	53	125.3	55	135
Replication 7																				
Tailings	15	94.2	40	79	18.2	87.2	25	69.2	51	102.7	27.3	51	28.5	74	20	75	30.3	87.5	ND	ND
Contaminated Soil	30.1	115	25.5	111	30.1	110	22	100.7	22.4	109.7	22	98.5	32.5	101.5	36.3	110.5	23.5	113.5	ND	40
PGC Soil	50	101	55.2	107.5	42.3	87	48.7	116.5	29.3	77.5	39.7	110.7	27.5	94.2	40.3	100.5	70.2	109.5	76.3	91
Replication 8																				
Tailings	36.8	76	34.5	91.4	19	92.1	21.3	111.2	28.8	117	29	92.3	31.5	92	19.2	85	42	97.5	ND	ND
Contaminated Soil	33	100.2	27.3	115.2	42.5	108.7	28.5	119.5	33.7	124.2	36	103.5	35.5	124	28	101.2	29.2	106.5	10	35.2
PGC Soil	56.7	110.5	61.5	126	25	96	45.7	103	33.2	109.7	32	124	47	119.2	48.5	119.5	67.5	129.5	69.5	118.5

ND = No Data

Table 31. Measured pH (s.u., 70 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	8.2	8.1	8.1	8.2	8.0	8.0	8.0	8.3	8.0	8.4	8.3	8.3	8.7	8.1	7.8	7.9	8.0	8.3	2.1	2.0
Contaminated Soil	8.2	8.3	8.5	8.4	8.3	8.5	8.1	8.0	8.0	7.9	8.2	8.2	7.6	8.0	8.5	8.3	8.4	8.5	5.0	5.1
PGC Soil	8.2	8.4	8.6	8.6	8.0	8.5	8.6	8.6	8.4	8.6	8.7	8.6	8.5	8.5	8.5	8.5	8.1	8.4	8.6	8.5
Replication 2																				
Tailings	8.2	8.1	8.1	8.1	8.1	8.3	8.2	8.3	8.5	8.4	8.3	8.6	8.3	8.3	8.2	8.4	8.3	8.5	2.0	2.1
Contaminated Soil	8.3	8.5	8.4	8.2	8.5	8.6	8.5	8.3	8.4	8.3	8.1	8.0	8.4	8.3	8.4	8.5	8.0	7.9	5.0	5.2
PGC Soil	8.5	7.8	8.5	8.4	8.3	8.2	8.4	8.8	8.3	8.5	8.4	8.7	8.8	8.9	8.6	8.6	8.8	8.5	8.6	8.4
Replication 3																				
Tailings	8.3	8.1	8.4	8.2	8.1	8.2	7.8	7.5	8.4	8.5	8.3	8.5	7.9	8.4	8.4	8.3	8.0	8.2	2.3	1.9
Contaminated Soil	8.2	8.3	8.5	8.4	8.3	8.5	8.1	8.0	8.0	7.9	8.1	8.2	7.9	8.0	8.5	8.6	8.5	8.4	5.1	5.0
PGC Soil	8.3	8.6	8.4	8.5	8.5	8.5	8.7	8.4	8.2	8.7	8.6	8.5	8.8	9.1	8.6	8.9	8.4	8.4	7.7	8.3
Replication 4																				
Tailings	8.4	8.2	8.1	8.3	8.1	8.1	7.7	8.3	7.9	8.1	7.9	9.3	7.8	8.2	8.0	8.3	8.1	8.0	2.1	2.0
Contaminated Soil	8.1	8.2	8.4	8.4	8.0	8.4	8.1	8.2	8.5	8.3	8.1	8.3	8.2	8.3	8.1	8.3	8.4	8.4	5.0	5.3
PGC Soil	8.5	7.9	8.6	8.1	8.0	8.1	8.4	8.5	8.5	8.6	8.4	8.3	8.4	8.7	8.7	8.4	8.1	8.5	8.2	8.4
Replication 5																				
Tailings	8.2	8.2	8.1	8.0	8.1	7.9	8.2	8.0	8.1	8.3	8.1	8.2	8.1	7.8	8.2	8.1	8.1	8.1	2.0	1.8
Contaminated Soil	8.2	8.3	8.5	8.4	8.3	8.5	8.1	8.0	8.0	7.9	8.1	8.2	7.9	8.0	8.5	8.6	8.5	8.4	4.9	5.0
PGC Soil	8.4	7.6	8.6	8.5	8.2	8.3	7.4	8.5	8.5	8.3	8.5	8.1	9.0	8.5	8.7	8.3	8.6	9.1	8.7	8.5
Replication 6																				
Tailings	8.2	8.2	8.0	8.1	7.9	8.0	7.8	8.2	7.9	8.4	8.1	8.2	8.3	8.2	8.4	7.8	8.1	8.0	1.9	2.1
Contaminated Soil	8.1	8.2	8.4	8.5	8.1	8.2	7.3	8.4	8.4	8.6	8.5	8.3	8.2	8.3	8.1	8.3	8.4	8.4	5.0	5.3
PGC Soil	8.4	8.4	8.4	9.0	8.6	8.2	8.9	8.2	8.5	8.1	8.9	8.8	8.6	8.7	8.6	8.1	8.7	8.7	8.2	8.1
Replication 7																				
Tailings	7.9	7.8	8.0	8.2	8.1	8.0	8.2	7.9	8.1	7.7	8.7	8.0	7.9	7.8	8.1	7.8	8.0	8.1	2.0	1.9
Contaminated Soil	8.1	8.2	8.4	8.4	8.0	8.4	8.1	8.2	8.5	8.3	8.1	7.9	7.9	8.0	8.5	8.4	8.5	8.5	5.0	5.2
PGC Soil	8.2	8.4	8.4	8.6	8.4	8.6	8.7	8.5	8.3	8.5	8.5	8.5	8.6	8.5	8.6	8.4	8.1	8.3	7.9	8.3
Replication 8																				
Tailings	8.2	8.1	8.0	8.1	8.0	8.3	8.3	8.1	8.2	8.0	8.1	8.2	8.2	8.2	8.1	8.1	8.1	8.1	2.0	2.0
Contaminated Soil	8.2	8.3	8.5	8.4	8.3	8.5	8.1	8.0	8.0	7.9	8.1	8.2	7.9	8.0	8.5	8.6	8.5	8.4	4.9	4.9
PGC Soil	8.4	8.4	8.6	8.3	7.8	8.6	8.5	8.8	8.5	8.3	8.3	8.4	8.3	8.5	8.5	8.6	8.3	8.4	7.9	8.6

Table 32. Aboveground height (height from soil to longest leaf (mm), 111 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	210	110	225	332	235	160	195	321	330	390	213	205	230	485	112	314	140	200	ND	ND
Contaminated Soil	220	95	335	345	330	320	95	230	160	230	273	145	150	122	258	137	125	310	ND	124
PGC Soil	522	544	415	720	600	590	380	529	320	655	305	550	340	486	430	569	360	500	350	521
Replication 2																				
Tailings	285	300	175	175	75	90	62	228	244	480	185	130	200	260	60	285	120	117	ND	ND
Contaminated Soil	255	217	440	302	150	260	280	277	175	133	294	120	345	320	214	165	174	190	0.5	65
PGC Soil	470	600	465	600	393	675	312	310	322	570	293	431	310	525	345	550	271	235	430	555
Replication 3																				
Tailings	46	330	237	365	65	80	160	339	224	310	130	180	242	440	80	80	93	150	ND	ND
Contaminated Soil	182	560	452	226	425	310	306	340	240	205	164	185	400	215	235	171	117	175	0.5	62
PGC Soil	310	530	296	490	302	563	245	546	254	452	305	410	325	640	372	580	444	562	410	540
Replication 4																				
Tailings	189	140	253	225	116	330	80	122	145	222	90	80	185	230	225	147	60	151	ND	ND
Contaminated Soil	135	211	470	212	342	225	229	286	285	276	47	237	150	235	172	245	183	171	40	55
PGC Soil	174	540	310	605	305	427	240	401	383	460	190	330	330	625	310	550	329	590	241	532
Replication 5																				
Tailings	156	144	233	343	63	101	150	227	131	290	82	220	136	481	42	65	100	116	ND	ND
Contaminated Soil	145	292	307	176	245	190	345	114	325	160	277	240	230	210	283	208	116	107	ND	85
PGC Soil	306	550	302	602	403	420	240	405	264	485	305	343	258	445	306	335	335	455	251	470
Replication 6																				
Tailings	30	368	185	304	197	216	150	167	245	295	35	168	168	246	66	87	110	142	ND	ND
Contaminated Soil	115	306	400	395	373	240	310	244	195	350	130	167	190	362	245	210	245	115	ND	54
PGC Soil	270	571	281	468	272	499	332	320	345	567	215	400	236	354	260	493	368	506	261	494
Replication 7																				
Tailings	153	334	206	357	132	145	150	159	165	394	83	203	166	91	20	74	104	135	ND	ND
Contaminated Soil	221	261	290	145	190	230	290	198	220	142	333	109	247	183	220	184	100	144	ND	70
PGC Soil	253	600	286	650	209	295	237	345	263	336	180	440	251	295	290	529	260	539	265	404
Replication 8																				
Tailings	122	310	88	243	80	150	264	230	200	335	46	70	170	320	70	330	90	120	ND	ND
Contaminated Soil	310	230	305	274	240	165	330	180	245	206	271	189	305	192	245	207	221	185	ND	95
PGC Soil	258	451	325	600	363	348	290	465	239	475	195	410	230	495	305	439	267	480	206	546

ND = No Data

Table 33. Maximum root depth (length of longest root (mm), 111 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	130	110	130	125	120	123	125	321	115	110	110	110	113	120	115	104	125	115	ND	ND
Contaminated Soil	90	70	105	115	115	125	80	105	70	90	85	60	95	90	105	85	25	105	ND	1
PGC Soil	120	120	105	100	125	115	125	112	120	130	101	119	103	110	103	96	103	100	118	115
Replication 2																				
Tailings	115	120	128	105	115	100	130	121	110	105	125	110	125	135	100	118	114	105	ND	ND
Contaminated Soil	110	90	110	115	87	110	80	110	80	105	113	100	110	105	93	102	76	90	1	1
PGC Soil	122	120	105	95	115	130	105	115	130	115	110	115	115	105	110	110	100	90	125	110
Replication 3																				
Tailings	40	120	127	120	100	120	112	125	106	97	120	97	120	104	115	102	102	110	ND	ND
Contaminated Soil	100	150	120	116	117	120	124	120	125	140	100	115	100	100	120	110	71	110	1	30
PGC Soil	123	120	100	96	230	120	110	107	130	125	110	114	100	105	117	100	115	108	105	109
Replication 4																				
Tailings	120	110	131	115	120	128	120	110	116	105	115	105	120	120	120	119	90	95	ND	ND
Contaminated Soil	105	90	125	125	123	105	120	114	135	117	1	105	105	105	97	107	95	95	2	2
PGC Soil	114	95	105	103	110	120	115	120	122	120	110	105	90	115	115	105	110	111	120	115
Replication 5																				
Tailings	112	110	120	127	120	125	110	116	100	126	108	105	110	120	75	110	95	105	ND	ND
Contaminated Soil	105	110	127	110	115	110	100	110	110	110	100	120	112	97	112	100	103	54	ND	0
PGC Soil	125	120	120	115	115	112	127	110	115	120	112	125	100	110	114	105	100	105	105	115
Replication 6																				
Tailings	5	120	134	125	135	123	120	105	110	100	95	115	115	110	115	103	110	120	ND	ND
Contaminated Soil	115	115	120	110	120	110	110	110	120	120	160	120	105	97	120	95	100	108	ND	54
PGC Soil	115	125	103	105	130	125	115	100	124	121	122	95	103	95	110	110	113	97	120	105
Replication 7																				
Tailings	125	120	125	125	120	120	110	100	105	100	100	115	130	115	90	120	105	103	ND	ND
Contaminated Soil	70	100	130	120	119	105	120	105	130	110	125	105	96	100	140	85	55	105	48	55
PGC Soil	109	115	100	110	120	120	106	105	121	125	112	111	120	115	111	100	90	110	105	120
Replication 8																				
Tailings	122	120	120	170	120	105	110	120	120	100	115	120	120	150	105	100	105	125	ND	ND
Contaminated Soil	105	115	115	130	110	100	110	120	115	115	115	100	105	100	105	95	45	70	ND	2
PGC Soil	125	120	105	100	110	107	120	115	115	125	130	130	109	100	110	120	100	105	115	115

ND = No Data

Table 34. Root distribution (number of roots at 5 cm depth, 111 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	40	17	12	25	10	15	27	30	40	35	20	11	40	35	28	27	7	13	ND	ND
Contaminated Soil	7	6	30	13	7	6	7	8	7	23	5	2	10	3	5	1	2	8	0	0
PGC Soil	35	125	100	75	100	80	70	25	50	50	45	25	30	32	15	35	30	48	100	50
Replication 2																				
Tailings	25	15	30	15	3	3	0	11	20	5	6	3	13	50	8	16	9	1	ND	ND
Contaminated Soil	5	3	7	30	10	15	3	30	3	5	9	1	20	9	18	6	20	10	0	0
PGC Soil	50	150	60	60	60	65	25	125	25	71	40	70	80	95	80	48	75	38	120	25
Replication 3																				
Tailings	49	15	23	30	40	15	15	18	17	20	50	10	25	22	7	7	10	10	ND	ND
Contaminated Soil	60	12	80	25	25	35	40	20	30	25	7	20	38	30	40	5	1	35	0	6
PGC Soil	55	45	115	30	100	25	35	34	55	25	25	40	40	25	20	25	45	35	40	115
Replication 4																				
Tailings	25	5	35	12	15	36	10	10	12	18	2	8	25	25	30	40	10	6	ND	ND
Contaminated Soil	2	15	50	30	40	20	15	35	40	30	0	8	20	6	20	30	10	5	0	0
PGC Soil	44	26	90	25	100	35	25	25	80	40	74	10	20	45	60	40	46	32	50	40
Replication 5																				
Tailings	5	12	25	25	5	12	5	15	5	35	1	12	30	45	4	12	5	12	ND	ND
Contaminated Soil	3	18	25	20	5	25	15	11	15	17	5	35	10	12	5	35	5	3	0	0
PGC Soil	40	35	25	70	40	60	25	40	90	50	80	18	20	45	60	50	60	25	50	85
Replication 6																				
Tailings	3	20	45	13	45	15	37	15	45	19	3	10	60	45	5	5	12	13	ND	ND
Contaminated Soil	30	30	45	109	45	30	100	37	72	35	20	35	35	50	35	35	60	10	0	1
PGC Soil	47	70	45	55	30	70	45	25	20	47	40	27	5	35	65	55	35	50	50	175
Replication 7																				
Tailings	19	30	49	35	20	18	25	12	50	30	10	19	90	25	4	10	25	12	ND	ND
Contaminated Soil	10	25	60	30	40	35	40	35	20	13	45	15	60	13	20	5	4	6	0	1
PGC Soil	50	80	70	80	50	20	20	35	60	0	50	40	120	70	30	47	30	70	120	150
Replication 8																				
Tailings	30	8	20	20	36	6	50	20	44	40	6	4	100	200	11	4	16	4	ND	ND
Contaminated Soil	30	19	100	100	50	14	60	24	55	50	30	40	50	19	135	25	0	22	0	0
PGC Soil	70	70	60	105	40	60	100	50	100	65	35	60	90	78	60	60	47	40	75	150

ND = No Data

Table 35. Root distribution (number of roots at 10 cm depth, 111 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	20	2	9	30	5	25	16	25	50	40	10	9	55	100	2	23	15	30	ND	ND
Contaminated Soil	0	0	3	9	2	6	0	2	6	19	3	0	0	0	2	0	0	7	0	0
PGC Soil	50	150	125	50	70	100	90	35	100	100	39	30	45	115	20	40	40	38	150	60
Replication 2																				
Tailings	30	20	40	19	6	5	0	19	5	9	8	5	26	60	0	14	5	0	ND	ND
Contaminated Soil	0	5	15	27	0	20	0	35	0	6	10	1	25	13	0	3	0	0	0	0
PGC Soil	60	70	80	120	65	130	60	75	90	157	40	75	70	80	40	30	50	15	210	100
Replication 3																				
Tailings	0	25	10	40	30	10	20	25	31	0	20	0	30	35	5	5	2	10	ND	ND
Contaminated Soil	18	5	90	20	10	13	25	25	15	21	1	12	40	5	0	2	0	1	0	0
PGC Soil	60	50	140	45	60	50	40	50	70	35	10	55	50	50	11	60	30	20	50	150
Replication 4																				
Tailings	30	10	60	9	10	35	5	10	12	20	4	7	45	40	15	10	1	2	ND	ND
Contaminated Soil	2	10	60	20	50	10	12	30	30	25	0	6	6	10	0	11	1	1	0	0
PGC Soil	70	22	110	80	115	40	47	35	80	60	60	10	30	65	50	20	40	30	70	35
Replication 5																				
Tailings	5	13	45	27	0	13	1	15	5	37	5	15	50	70	0	3	7	5	ND	ND
Contaminated Soil	0	30	35	12	20	20	5	3	10	15	1	35	5	20	10	3	1	0	0	0
PGC Soil	60	50	50	60	50	40	40	60	80	75	50	30	20	85	30	50	35	18	100	200
Replication 6																				
Tailings	0	47	49	13	60	25	48	15	60	30	0	6	80	50	2	5	6	13	ND	ND
Contaminated Soil	15	15	55	100	30	40	75	25	40	25	10	27	40	45	20	15	40	5	0	0
PGC Soil	70	160	100	150	30	150	65	40	30	110	55	0	5	0	25	80	40	0	75	250
Replication 7																				
Tailings	20	45	85	55	20	25	30	18	75	100	4	25	110	40	0	10	10	12	ND	ND
Contaminated Soil	0	15	50	17	55	20	30	16	15	7	30	7	45	12	15	0	0	3	0	0
PGC Soil	100	70	150	100	70	15	100	30	180	100	55	100	130	200	17	150	0	150	170	300
Replication 8																				
Tailings	100	9	10	20	25	20	50	100	71	60	2	2	200	200	6	15	9	15	ND	ND
Contaminated Soil	15	16	200	50	40	9	110	10	165	40	50	3	30	10	100	0	0	0	0	0
PGC Soil	70	105	65	160	45	120	110	50	190	65	50	120	90	180	65	65	89	45	100	180

ND = No Data

Table 36. Aboveground biomass (weight of aboveground production (g), 111 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	0.871	0.114	0.170	0.537	0.067	0.028	0.128	0.279	1.138	0.166	0.233	0.236	0.611	0.931	0.034	0.148	0.925	0.008	ND	ND
Contaminated Soil	0.138	1.174	0.447	0.437	0.141	0.130	0.137	0.013	0.038	0.212	0.112	1.162	0.133	0.383	0.021	0.039	0.116	0.123	ND	0.133
PGC Soil	1.795	0.504	0.601	2.823	2.826	0.080	2.688	0.846	1.820	0.831	0.467	1.712	0.438	0.839	1.422	1.333	0.035	2.062	0.378	1.025
Replication 2																				
Tailings	0.812	0.417	1.152	0.175	0.062	0.105	0.150	0.451	0.655	0.331	0.193	0.091	0.557	0.551	0.096	0.334	0.043	0.077	ND	ND
Contaminated Soil	0.312	0.464	0.744	0.517	0.143	0.515	0.085	0.932	0.111	0.028	0.466	0.215	1.182	0.495	0.209	0.266	0.023	0.240	ND	0.023
PGC Soil	4.790	3.726	3.573	3.876	3.244	1.744	0.759	1.504	2.117	2.332	0.913	1.301	1.889	1.542	3.288	2.241	4.683	1.933	3.570	2.020
Replication 3																				
Tailings	0.009	0.781	0.789	0.662	0.029	0.068	0.398	0.693	0.715	0.330	0.292	0.159	0.813	0.340	0.191	0.028	0.169	0.083	ND	ND
Contaminated Soil	0.430	0.753	1.662	0.757	1.025	0.773	1.487	0.654	1.275	0.651	0.201	0.303	0.880	0.654	0.650	0.292	0.443	0.390	0.119	0.088
PGC Soil	3.830	2.514	3.044	3.268	2.644	1.452	1.353	2.557	3.705	1.357	0.866	1.444	1.736	1.050	2.733	3.387	3.786	3.288	2.987	2.333
Replication 4																				
Tailings	0.678	0.053	2.187	0.396	0.005	0.680	0.112	0.232	0.092	0.244	0.044	0.029	0.418	0.464	0.193	0.018	0.001	0.078	ND	ND
Contaminated Soil	0.052	0.481	2.143	0.428	1.030	0.546	0.441	0.814	1.025	0.626	0.003	0.277	0.260	0.433	0.253	0.364	0.042	0.236	0.001	0.009
PGC Soil	2.051	1.577	4.226	2.496	1.858	1.045	0.839	0.886	2.041	2.581	0.650	0.426	0.979	2.208	3.156	2.619	1.996	2.114	1.378	1.998
Replication 5																				
Tailings	0.185	0.130	0.665	0.953	0.090	0.080	0.030	0.189	0.115	0.335	0.003	0.254	0.396	0.806	0.020	0.040	0.080	0.003	ND	ND
Contaminated Soil	0.068	0.489	1.271	0.418	0.548	0.783	0.421	0.180	0.744	0.141	0.183	0.789	0.592	0.219	0.127	0.198	0.121	0.150	0.010	0.060
PGC Soil	2.783	1.910	3.141	3.536	1.743	1.482	1.297	0.601	2.083	2.106	1.684	1.124	1.420	0.843	3.131	2.203	3.040	2.015	1.736	4.115
Replication 6																				
Tailings	0.041	0.854	1.181	0.499	0.598	0.339	0.612	0.176	1.114	0.580	0.063	0.191	0.689	0.539	0.131	0.129	0.176	0.179	ND	ND
Contaminated Soil	1.234	0.734	1.237	0.984	1.553	0.484	0.990	0.523	0.822	1.193	0.703	0.341	0.853	0.664	0.486	0.543	0.586	0.204	ND	0.263
PGC Soil	2.346	2.847	2.639	2.454	1.471	2.029	1.774	0.623	1.949	1.869	1.136	0.846	1.564	0.837	1.754	2.117	3.866	2.425	2.301	2.736
Replication 7																				
Tailings	0.050	0.789	1.240	0.707	0.150	0.057	0.442	0.120	1.122	0.527	0.020	0.163	0.612	0.056	0.001	0.030	0.041	0.023	ND	ND
Contaminated Soil	0.220	0.433	1.115	0.450	1.111	0.619	0.690	0.454	0.619	0.126	1.248	0.272	1.119	0.256	0.506	0.232	0.075	0.172	ND	0.016
PGC Soil	1.721	3.143	2.532	3.601	1.238	0.743	0.599	0.532	3.160	2.952	1.485	1.328	3.397	1.285	2.136	1.799	2.070	2.801	2.036	1.837
Replication 8																				
Tailings	0.463	0.798	0.092	0.447	0.022	0.190	0.612	0.373	0.350	0.664	0.001	0.022	0.869	0.844	0.046	0.490	0.008	0.093	ND	ND
Contaminated Soil	0.510	0.434	2.107	0.935	1.047	0.389	0.792	0.388	0.987	0.409	0.766	0.219	1.255	0.236	0.671	0.158	0.176	0.342	ND	0.010
PGC Soil	1.383	1.760	2.345	2.421	1.012	0.960	3.276	1.813	1.566	1.910	1.003	0.998	1.225	1.233	2.866	2.628	1.911	1.266	1.529	1.564

ND = No Data

Table 37. Belowground biomass (weight of belowground production (g), 111 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	0.682	0.031	0.485	0.769	0.112	0.075	0.042	0.414	1.301	0.188	0.004	0.411	0.652	0.352	0.024	0.274	0.037	0.154	ND	ND
Contaminated Soil	0.134	1.175	0.428	0.239	0.054	0.010	0.287	0.069	0.175	0.112	0.186	0.097	0.110	0.336	0.100	0.269	0.221	0.055	ND	0.149
PGC Soil	0.084	5.066	2.161	2.179	0.314	1.928	1.451	1.420	0.337	0.771	0.537	0.390	0.653	1.792	1.252	0.999	1.168	1.879	3.335	2.190
Replication 2																				
Tailings	1.129	0.868	4.112	0.495	0.262	0.117	0.076	0.513	0.971	0.629	0.302	0.090	1.134	2.157	0.084	0.470	0.048	0.321	ND	ND
Contaminated Soil	0.284	0.150	0.451	0.377	0.180	0.503	0.178	1.014	0.237	0.192	0.155	0.190	0.867	0.485	0.013	0.163	0.004	0.366	ND	0.001
PGC Soil	2.483	4.686	2.769	3.599	2.282	4.984	1.331	2.230	2.389	6.237	0.562	1.855	1.402	5.304	1.468	1.683	1.993	2.330	8.129	3.329
Replication 3																				
Tailings	0.124	0.406	1.079	1.592	0.133	0.121	0.344	0.993	1.202	0.770	0.587	0.190	1.319	0.691	0.279	0.071	0.119	0.163	ND	ND
Contaminated Soil	0.369	0.599	1.754	1.174	0.537	1.049	1.003	1.358	1.896	0.484	0.101	0.320	0.709	1.218	0.318	0.262	0.299	0.159	0.001	0.032
PGC Soil	4.111	4.104	2.209	5.415	2.033	4.124	2.500	5.606	4.814	2.945	1.081	3.866	1.848	1.667	1.949	3.856	2.529	4.590	3.762	6.877
Replication 4																				
Tailings	0.750	0.180	1.855	0.678	0.051	1.512	0.082	0.234	0.332	0.457	0.048	0.148	1.219	1.454	0.435	0.190	0.011	0.049	ND	ND
Contaminated Soil	0.051	0.573	1.905	0.421	0.939	1.121	0.183	0.882	0.580	0.652	0.001	0.558	0.213	0.405	0.234	0.838	0.039	0.194	0.001	0.001
PGC Soil	3.782	4.464	1.929	3.455	3.228	2.505	2.646	2.191	3.186	4.918	1.344	0.606	1.649	2.826	1.346	4.193	2.019	4.033	9.159	4.659
Replication 5																				
Tailings	0.135	0.223	0.763	2.352	0.085	0.148	0.050	0.285	0.262	0.885	0.035	0.595	1.047	1.839	0.040	0.012	0.180	0.142	ND	ND
Contaminated Soil	0.062	0.752	1.420	0.565	0.576	0.806	0.351	0.080	0.507	0.200	0.144	0.605	0.676	0.301	0.038	0.216	0.229	0.060	ND	0
PGC Soil	2.445	3.204	3.220	6.902	1.763	2.273	2.170	1.063	1.848	5.220	1.547	2.338	1.457	3.025	2.001	2.149	1.947	3.096	3.775	13.57
Replication 6																				
Tailings	0.075	1.899	2.627	1.029	1.460	0.914	1.611	0.350	1.044	1.208	0.170	0.443	1.664	1.380	0.322	0.233	0.234	0.524	ND	ND
Contaminated Soil	1.945	0.695	1.411	3.173	0.805	0.896	1.182	2.263	1.117	1.184	0.939	0.404	0.667	0.833	0.554	1.308	1.908	0.513	ND	0.001
PGC Soil	2.703	4.958	2.347	4.006	1.501	3.876	2.124	1.415	1.557	4.383	1.796	1.853	1.309	2.115	2.579	3.190	3.375	3.754	4.145	5.232
Replication 7																				
Tailings	0.266	2.318	3.022	2.491	0.203	0.613	0.787	0.187	2.316	1.710	0.054	0.190	2.236	0.343	0.001	0.145	0.201	0.234	ND	ND
Contaminated Soil	0.204	0.606	1.072	0.612	0.939	0.860	1.350	0.517	0.327	0.155	0.862	0.223	1.434	0.388	0.670	0.289	0.081	0.241	ND	0.001
PGC Soil	7.864	5.720	4.432	5.822	3.681	2.904	4.387	2.218	6.167	7.085	2.929	3.452	6.224	5.162	1.947	4.184	2.077	5.277	5.155	7.897
Replication 8																				
Tailings	1.370	1.826	0.402	1.198	0.064	0.707	0.744	0.756	0.416	1.526	0.001	0.079	1.806	3.638	0.124	0.998	0.037	0.504	ND	ND
Contaminated Soil	0.340	0.614	2.072	0.912	0.883	0.487	1.219	0.571	1.854	0.710	0.332	0.466	1.664	0.485	0.918	0.270	0.114	0.476	ND	0.001
PGC Soil	6.882	6.433	7.138	5.780	9.302	3.859	9.851	4.991	5.994	4.659	3.971	2.694	7.316	3.024	3.491	8.042	7.167	5.534	13.69	9.960

ND = No Data

Table 38. Measured pH (s.u., 111 day growth) in tailings, contaminated soil and Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO		Control	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																				
Tailings	8.0	8.0	7.8	7.8	7.8	8.0	7.8	7.9	7.9	7.8	8.3	7.9	7.9	7.7	7.7	7.5	7.8	7.7	2.0	1.9
Contaminated Soil	7.6	7.7	7.8	7.7	8.0	8.0	7.2	7.7	7.5	7.7	7.3	7.4	8.0	7.7	7.8	7.9	7.5	7.6	5.1	5.2
PGC Soil	8.1	8.0	8.2	8.1	8.3	8.0	8.2	8.3	8.2	8.1	7.9	8.0	8.1	7.9	8.0	7.7	8.0	7.9	7.2	7.0
Replication 2																				
Tailings	8.1	8.0	8.0	7.9	7.8	7.5	7.8	7.8	7.9	7.9	8.0	7.9	8.0	8.1	8.0	7.9	7.7	7.6	1.9	2.0
Contaminated Soil	8.1	7.5	7.8	8.0	8.3	8.0	7.9	7.8	7.7	7.9	7.7	7.8	8.2	8.2	8.0	7.9	7.7	7.6	4.9	5.1
PGC Soil	8.0	8.2	8.4	8.4	7.9	8.3	8.7	8.3	7.8	8.3	8.3	8.2	8.1	8.1	8.1	8.1	8.2	8.1	7.6	7.2
Replication 3																				
Tailings	7.7	7.9	7.7	8.0	7.8	7.8	7.9	7.9	7.8	7.7	7.7	8.0	8.0	7.6	8.2	7.7	7.9	7.6	2.0	2.1
Contaminated Soil	7.7	7.7	7.7	7.7	7.8	7.9	7.6	7.1	7.5	7.3	7.5	7.5	8.2	7.9	7.5	7.9	7.5	7.3	5.0	5.0
PGC Soil	8.0	8.0	8.3	8.1	8.3	8.2	8.4	8.5	7.9	8.0	8.2	8.3	8.2	7.8	8.0	7.9	8.2	8.0	7.3	7.1
Replication 4																				
Tailings	6.5	7.8	7.7	7.8	7.9	7.7	7.7	7.8	7.8	7.6	8.1	8.0	8.0	7.9	8.0	7.7	7.7	7.9	2.1	1.8
Contaminated Soil	7.8	7.7	8.0	7.9	8.1	8.1	8.0	7.5	7.5	7.6	8.0	8.0	7.8	8.2	8.2	8.0	7.7	7.4	5.1	4.9
PGC Soil	7.8	8.0	8.2	8.1	8.1	8.2	7.8	8.3	8.0	7.9	7.9	8.0	8.2	7.7	8.4	7.9	8.3	8.2	7.6	7.1
Replication 5																				
Tailings	8.0	7.8	7.9	7.7	7.7	7.8	7.7	7.9	7.8	7.8	8.0	8.0	7.8	8.0	7.9	7.7	7.6	7.8	1.8	2.2
Contaminated Soil	7.8	7.7	7.6	8.0	7.9	7.8	7.8	7.6	7.7	7.7	7.4	7.6	7.7	8.0	7.9	7.9	7.9	8.0	5.1	4.8
PGC Soil	8.0	7.8	7.9	8.3	8.0	8.1	8.1	8.5	8.1	8.2	8.1	8.0	8.0	8.4	7.8	8.2	8.1	8.2	7.3	7.3
Replication 6																				
Tailings	7.9	7.8	7.7	7.6	7.8	7.7	7.6	7.6	7.8	7.6	8.0	7.9	8.1	7.7	7.6	7.8	8.0	7.8	2.0	2.0
Contaminated Soil	7.6	7.7	7.4	7.8	8.0	7.8	7.1	7.8	7.7	7.5	7.9	7.5	8.2	7.7	7.2	8.1	7.5	7.5	5.2	5.0
PGC Soil	7.9	7.8	8.2	8.0	8.1	8.1	8.2	8.5	8.0	7.9	7.9	8.0	8.2	8.3	8.0	8.1	8.0	8.2	7.3	7.3
Replication 7																				
Tailings	7.9	7.7	8.0	7.8	8.1	7.9	8.0	7.8	8.2	8.1	8.3	8.2	8.1	8.0	7.9	7.8	8.0	7.8	1.9	2.0
Contaminated Soil	8.0	8.1	8.0	8.0	8.3	8.3	7.9	8.1	8.0	7.9	7.8	7.8	8.3	8.3	8.2	8.1	8.0	7.8	4.9	5.0
PGC Soil	7.7	8.0	8.3	8.1	8.5	8.2	8.6	8.4	8.2	8.0	8.1	8.2	8.4	8.4	8.1	8.3	8.3	8.1	7.1	7.2
Replication 8																				
Tailings	8.1	8.4	7.1	8.1	8.0	8.2	7.9	7.9	7.9	8.1	8.0	8.6	7.5	7.9	7.8	8.0	7.9	8.1	2.1	1.9
Contaminated Soil	8.4	8.2	7.8	8.0	8.3	8.2	8.4	7.8	8.3	8.1	8.2	7.5	8.4	7.6	8.5	7.5	8.8	7.8	5.2	5.0
PGC Soil	8.4	7.4	8.8	7.2	8.4	8.6	8.8	8.7	8.3	8.1	8.3	8.0	8.1	7.6	8.6	8.0	8.2	8.1	7.6	7.1

Table 39. Number of days required for emergence in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	8	8	8	8	7	9	8	8	8	8	7	8	7	8	8	8	9	9
2%	6	8	6	8	6	7	6	7	6	7	6	8	6	8	6	9	6	8
4%	7	7	7	8	7	8	7	8	7	7	7	9	7	8	7	8	7	7
6%	7	8	7	8	7	7	8	7	7	8	7	8	7	8	7	7	7	7
8%	7	9	7	9	7	7	7	9	7	8	8	8	7	8	7	8	8	8
10%	7	8	7	9	7	7	7	7	7	7	9	9	7	9	7	8	7	8
12%	7	7	8	9	8	8	7	7	7	7	8	10	7	7	7	8	8	8
Replication 2																		
0%	7	8	7	7	7	8	7	8	8	8	8	7	7	8	7	8	7	8
2%	7	7	7	7	7	7	8	8	7	7	7	8	7	8	8	8	8	8
4%	7	8	8	8	7	8	8	9	7	7	8	8	8	8	8	8	8	8
6%	7	8	8	8	7	8	7	7	7	8	8	9	7	8	7	8	8	10
8%	8	8	7	7	7	8	7	9	7	8	7	8	7	9	7	8	9	8
10%	7	8	7	7	7	8	7	8	8	8	8	7	7	7	7	8	8	8
12%	8	9	7	7	9	8	8	9	7	9	9	9	7	7	8	8	8	8
Replication 3																		
0%	8	7	7	9	7	8	8	7	7	7	7	8	7	8	8	8	8	8
2%	8	7	7	8	7	8	7	7	7	7	7	8	8	8	7	8	7	8
4%	7	8	8	7	8	7	7	7	8	8	8	8	8	8	8	9	8	8
6%	6	8	7	8	7	9	7	8	7	9	8	8	8	8	7	8	8	8
8%	7	7	7	8	7	8	8	8	7	7	8	8	9	8	9	8	8	8
10%	7	8	7	8	7	8	8	7	7	8	8	8	7	7	7	8	8	8
12%	9	8	7	7	7	8	8	10	7	9	8	8	7	8	8	8	7	8

Continued ⟶

Table 39. Number of days required for emergence in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	8	9	8	5	8	8	9	8	8	5	8	5	8	5	8	6	8	6
2%	7	8	8	8	8	7	8	8	7	10	8	8	7	9	7	6	8	6
4%	7	8	7	8	7	8	7	9	7	8	7	8	7	8	8	6	8	6
6%	8	8	7	8	7	8	7	8	7	8	7	8	7	8	7	6	8	6
8%	8	8	7	8	8	8	7	8	7	8	8	8	7	7	7	6	7	6
10%	7	8	7	8	7	7	8	9	7	8	8	8	7	7	7	6	7	6
12%	7	8	7	8	7	8	7	7	7	7	8	9	7	7	7	7	7	8
Replication 5																		
0%	8	8	8	8	7	8	8	8	8	8	7	8	10	10	8	8	10	8
2%	7	7	7	8	8	8	7	7	7	7	8	8	8	8	8	8	8	8
4%	7	8	7	8	7	7	8	8	7	7	8	7	7	7	7	8	8	8
6%	8	7	7	7	7	8	7	7	7	7	8	7	8	8	8	8	8	8
8%	7	8	8	8	7	8	7	7	7	7	8	8	8	8	8	8	7	8
10%	9	7	8	7	7	7	8	7	8	7	8	10	7	7	9	8	7	7
12%	7	7	7	7	7	7	8	8	7	8	8	8	7	7	7	8	7	7

Table 40. Germination (number of seedlings emerged/15 seeds, 14 day post-emergence) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	15	15	15	15	15	9	15	11	15	15	15	12	15	15	15	12	15	15
2%	15	15	15	11	15	15	15	9	15	15	15	15	15	15	15	7	15	10
4%	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
6%	15	15	15	15	15	15	15	13	15	10	15	12	15	8	15	15	15	15
8%	15	9	15	10	15	9	15	11	15	10	15	9	15	15	15	15	15	12
10%	15	15	15	15	15	15	15	10	15	15	15	13	15	15	15	15	15	15
12%	15	10	15	15	15	12	15	11	15	15	15	9	15	12	15	10	15	15
Replication 2																		
0%	15	14	15	15	15	15	15	15	15	10	15	10	15	15	15	15	15	15
2%	15	15	15	12	15	15	15	15	15	15	15	15	15	15	15	15	15	15
4%	15	11	15	15	15	11	15	15	15	10	15	15	15	15	15	15	15	15
6%	15	15	15	15	15	10	15	15	15	15	15	9	15	15	15	11	15	10
8%	15	12	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	10
10%	15	15	15	11	15	15	15	15	15	15	15	15	15	10	15	15	15	13
12%	15	15	15	15	15	13	15	12	15	15	15	11	15	12	15	15	15	15
Replication 3																		
0%	15	15	15	15	15	12	15	15	15	15	15	15	15	15	15	15	15	7
2%	15	15	15	15	15	10	15	15	15	15	15	9	15	15	15	15	15	15
4%	15	10	15	15	15	15	15	15	15	14	15	15	15	13	15	12	15	12
6%	10	15	13	15	15	10	15	15	15	15	15	15	15	12	13	14	15	13
8%	15	15	15	15	15	12	15	15	15	13	15	12	15	15	15	15	15	15
10%	15	15	15	13	15	13	15	15	15	15	15	12	15	15	15	9	15	13
12%	15	15	15	12	15	13	15	8	15	12	15	9	15	15	15	15	15	15

Continued →

Table 40. Germination (number of seedlings emerged/15 seeds, 14 day post-emergence) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	3	6	15	15	15	15	7	7	15	15	10	15	15	15	15	15	15	10
2%	15	9	15	11	6	8	8	8	15	7	15	13	15	15	15	7	15	15
4%	15	12	15	11	15	11	11	11	15	15	15	8	15	15	15	9	15	15
6%	15	9	15	11	15	10	11	11	15	9	9	15	15	15	15	9	15	15
8%	15	15	15	10	15	14	7	7	15	13	15	8	15	15	15	10	15	15
10%	15	13	15	12	15	15	13	13	15	10	10	13	15	15	15	8	15	12
12%	15	9	15	13	15	10	14	14	15	10	15	4	15	15	15	13	15	15
Replication 5																		
0%	6	12	15	7	4	8	11	11	9	13	15	15	4	11	15	15	9	11
2%	15	15	7	15	9	12	15	15	15	15	10	9	7	10	7	15	15	10
4%	15	15	15	15	15	15	9	9	15	11	10	12	15	14	15	15	12	15
6%	15	13	15	15	15	6	9	9	13	15	15	11	8	7	15	15	9	8
8%	8	12	15	8	12	12	11	11	11	15	15	15	4	15	12	9	15	15
10%	12	15	8	12	12	11	11	11	15	12	12	12	15	14	15	15	15	15
12%	15	15	15	12	15	15	15	15	15	9	15	15	15	15	15	15	15	10

Table 41. Survival (number of seedlings survived/emerged, 14 day post-emergence) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	15	15	15	15	15	9	15	11	15	15	15	12	15	15	15	12	15	15
2%	15	15	15	11	15	15	15	9	15	15	15	15	15	15	15	7	15	10
4%	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
6%	15	15	15	15	15	15	15	13	15	10	15	12	15	8	15	15	15	15
8%	15	9	15	10	15	9	15	11	15	10	15	9	15	15	15	15	15	12
10%	15	15	15	15	15	15	15	10	15	15	15	13	15	15	15	15	15	15
12%	15	10	15	15	15	12	15	11	15	15	15	9	15	12	15	10	15	15
Replication 2																		
0%	15	14	15	15	15	15	15	15	15	10	15	10	15	15	15	15	15	15
2%	15	15	15	12	15	15	15	15	15	15	15	15	15	15	15	15	15	15
4%	15	11	15	15	15	11	15	15	15	10	15	15	15	15	15	15	15	15
6%	15	15	15	15	15	10	15	15	15	15	15	9	15	15	15	11	15	10
8%	15	12	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	10
10%	15	15	15	11	15	15	15	15	15	15	15	15	15	10	15	15	15	13
12%	15	15	15	15	15	13	15	12	15	15	15	11	15	12	15	15	15	15
Replication 3																		
0%	15	15	15	15	15	12	15	15	15	15	15	15	15	15	15	15	15	7
2%	15	15	15	15	15	10	15	15	15	15	15	9	15	15	15	15	15	15
4%	15	10	15	15	15	15	15	15	15	14	15	15	15	13	15	12	15	12
6%	10	15	13	15	15	10	15	15	15	15	15	15	15	12	13	14	15	13
8%	15	15	15	15	15	12	15	15	15	13	15	12	15	15	15	15	15	15
10%	15	15	15	13	15	13	15	15	15	15	15	12	15	15	15	9	15	13
12%	15	15	15	12	15	13	15	8	15	12	15	9	15	15	15	15	15	15

Continued →

Table 41. Survival (number of seedlings survived/emerged, 14 day post-emergence) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	3	6	15	15	15	15	7	7	15	15	10	15	15	15	15	15	15	10
2%	15	9	15	11	6	8	8	8	15	7	15	13	15	15	15	7	15	15
4%	15	12	15	11	15	11	11	11	15	15	15	8	15	15	15	9	15	15
6%	15	9	15	11	15	10	11	11	15	9	9	15	15	15	15	9	15	15
8%	15	15	15	10	15	14	7	7	15	13	15	8	15	15	15	10	15	15
10%	15	13	15	12	15	15	13	13	15	10	10	13	15	15	15	8	15	12
12%	15	9	15	13	15	10	14	14	15	10	15	4	15	15	15	13	15	15
Replication 5																		
0%	6	12	15	7	4	8	11	11	9	13	15	15	4	11	15	15	9	11
2%	15	15	7	15	9	12	15	15	15	15	10	9	7	10	7	15	15	10
4%	15	15	15	15	15	15	9	9	15	11	10	12	15	14	15	15	12	15
6%	15	13	15	15	15	6	9	9	13	15	15	11	8	7	15	15	9	8
8%	8	12	15	8	12	12	11	11	11	15	15	15	4	15	12	9	15	15
10%	12	15	8	12	12	11	11	11	15	12	12	12	15	14	15	15	15	15
12%	15	15	15	12	15	15	15	15	15	9	15	15	15	15	15	15	15	10

Table 42. Shoot height (height from soil to longest leaf (mm), 14 day post-emergence) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	145	256.2	132.2	204	109.2	185	126	187	102	206.5	118	170.5	135	175	66.5	210.7	79	203
2%	50.7	177	52.5	157.7	17.5	164.7	48.2	194.2	51	191.2	61	205	35	185	72	140	100	193
4%	73.7	178.2	67.7	141.7	28	155.5	97.5	193	115	177.2	79	192	67	157	100	170	87	193
6%	60.2	198.2	65	192	34	146.7	44.5	139	93	110	77	144	54	133	85	131	89	169
8%	32.7	161.2	50	156.2	34	111	52	153.5	58	126	47	132	43	116	46	146	66	138
10%	68	105	99	133	55	80	75	110	60	185	50	107	36	95	49	123	43	109
12%	56	149	79	159	31	91.2	56	160	61	177	61	121	37.5	126	39	115	47	116
Replication 2																		
0%	80.5	217	127.5	201.7	149.2	164	114.5	182.2	127.5	233.5	121.2	216.7	138.2	184.7	95.2	208.7	86.2	204.2
2%	78.7	162.5	55	128.7	86.7	147.2	98.7	152	64.2	182.5	85	177.5	137	178.7	71.5	155	104.2	165
4%	93.5	98.2	67.2	150.7	45.2	113	72	135.2	88	155.5	66.2	163.7	54.5	121.2	51.2	147.7	97.2	183
6%	44.5	125	63.2	145.7	20	133.5	67.2	102	96	124.5	45	82.2	43.2	105	51	91.2	84.2	94.7
8%	30.7	102.5	52.2	140	49.5	141.2	55.2	112.7	57.2	127.5	63.2	154	42	128	72	105	50.2	111.5
10%	39.5	137.5	103.2	124.2	16	97	38.2	104.2	30.2	161.5	31	145.2	28.3	111.7	25	89.5	34	107.2
12%	23.7	89.5	56	153.2	28.2	88.2	19.2	84.5	29	116.7	33.5	81.5	33.2	107.7	34	77.7	46.5	88
Replication 3																		
0%	67.2	187.7	96	180.2	98	144.5	96.5	194.5	96	194.5	91.5	186.7	96.2	148.5	80	136.5	85.8	180.5
2%	55.2	198.2	75.5	145	42.2	180	67.7	136	48.5	141	71.8	179.2	42.2	160.8	77	152.5	98.7	155.5
4%	62	138	71.2	147.2	28	137	57.2	171.5	58.2	149.2	65.8	129	43.8	87.5	35.8	95	49	127.8
6%	28.8	130.2	51.2	109.8	31	98.2	28.8	140.2	80.5	152.8	59.5	110	43.3	88	28.5	90.2	51.5	91.5
8%	29	117.2	57	140.7	21.2	101.5	42.8	121.5	33	137.2	45	78.5	25	92.5	38.2	97.8	27.5	106.7
10%	30	102.7	82	110.8	45	114.7	29.2	99	40.8	138.5	41.2	66.5	28.8	93.7	24.5	78.8	33	113.5
12%	27.5	95.5	56.5	129.5	26.5	94.2	21	80.7	25	93.2	33.8	101	42	102.8	36.2	85.5	28.5	97.2

Continued →

Table 42. Shoot height (height from soil to longest leaf (mm), 14 day post-emergence) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	19.5	112	69.5	128.5	59.3	140.5	54.4	128	47.3	97	30.3	140.5	53.3	121.3	42.8	192	48.3	123.7
2%	86.8	95.5	34.9	101.3	38.3	100	85.5	113	132.8	64.5	91.3	152.3	54.8	123.7	26.3	64	25.5	50.8
4%	97.5	92.8	64.3	136.3	36	101	34.7	168.8	67.3	113	68.3	108.2	59.5	85.2	61.5	109.8	67	50.8
6%	65	119.8	32.3	117.5	38.5	81	51.8	97	32.8	113.2	47.7	93.3	45.3	75.8	59.3	101.8	41.3	80.8
8%	47.2	72.5	36.7	105.2	51.3	85.8	57.5	139.8	76.3	129.3	46.3	72.5	33	87	43.5	155.5	36.5	72.8
10%	39	36.3	82.3	214.5	15.8	91	46.5	102.5	28.5	83.5	30.2	73	22.3	101	26	64.2	20.5	76.3
12%	28	108.3	23.7	120.5	25	95.4	29.5	76.6	36.3	103.2	30.2	65.2	26.2	85.5	52.5	91.3	44	122.5
Replication 5																		
0%	170	252.2	133.2	156.2	157.5	192	88	248	77	152.2	96.5	174	126.5	163.7	109.2	167.2	93.2	190
2%	126	169.5	119	190.7	77	152.5	79	172.2	93.7	123	101.2	164.2	77.5	166.5	106.2	166.5	93.7	165.2
4%	58.7	127.5	118.7	128.5	70.5	147.7	81.5	160	92.5	183.5	57	182.5	52.2	123.2	88.5	236.2	91.2	147
6%	78.7	103	58.2	153.7	24.7	108.7	62.2	128.7	59.7	136.2	73	135.7	38.7	86	62.7	141.2	75	154
8%	34.7	105.2	51.2	159	55.2	80.7	70.2	117.2	22	183	37.5	140	29.2	88.7	26.2	88	46.5	116.5
10%	32	95	98	126.2	37.5	105.2	32.5	102.7	23	81	30	131.2	21	71.2	28.8	65.5	36.2	74.7
12%	46.5	90.3	42	102	26	123.5	43.7	98.2	39.2	96.5	40.2	92.5	28.3	108.5	62.2	84.2	33	79.7

Table 43. Aboveground height (height from soil to longest leaf (mm), 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	184	235	240	300	201	340	213	300	230	365	235	249	210	300	191	370	135	305
2%	273	305	180	257	154	330	179	255	315	225	120	370	155	245	90	335	197	280
4%	459	255	120	240	186	200	190	245	95	282	135	211	145	250	135	205	127	190
6%	247	226	105	260	161	236	166	335	165	185	130	257	141	335	133	210	161	175
8%	197	305	125	215	90	140	200	290	180	240	163	210	195	195	121	175	131	200
10%	126	170	135	270	155	131	130	195	155	315	172	165	100	166	143	205	144	160
12%	113	205	125	200	205	135	130	220	210	245	114	235	165	160	133	300	135	173
Replication 2																		
0%	212	350	253	409	145	215	178	277	175	340	239	305	242	340	177	315	187	278
2%	176	300	112	309	196	280	152	196	174	302	125	315	217	244	145	205	125	285
4%	200	265	204	205	203	261	226	296	141	332	128	304	145	190	145	235	198	315
6%	233	195	133	194	85	285	160	259	255	325	173	275	210	155	295	269	122	186
8%	178	411	176	355	208	455	125	234	155	219	185	252	100	138	116	194	160	171
10%	235	311	185	264	99	150	160	170	174	300	149	240	95	180	139	212	165	185
12%	125	200	178	330	110	135	138	205	65	158	167	230	192	139	120	195	178	125
Replication 3																		
0%	144	310	147	390	214	230	365	240	135	381	121	337	176	195	165	146	160	245
2%	186	353	194	177	132	270	190	245	55	175	145	228	99	198	159	220	215	216
4%	95	195	130	210	209	330	100	175	96	300	200	210	135	121	95	165	127	145
6%	202	255	114	150	135	174	95	181	130	235	170	177	150	125	135	115	145	113
8%	105	210	102	320	77	120	78	145	207	230	175	130	220	224	110	110	134	190
10%	200	165	162	158	100	155	89	120	97	180	100	210	59	250	100	122	112	200
12%	110	135	137	225	111	205	47	180	106	135	170	205	160	130	100	108	132	103

Continued →

Table 43. Aboveground height (height from soil to longest leaf (mm), 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	128	300	145	200	145	289	171	320	136	226	95	211	172	218	130	150	185	209
2%	136	192	93	169	235	194	131	215	162	244	210	293	130	195	175	203	86	164
4%	193	190	155	223	170	140	135	305	180	210	203	304	140	240	99	214	103	153
6%	146	220	143	200	110	117	113	130	88	205	145	298	88	112	122	211	106	215
8%	170	200	161	175	98	137	90	249	90	208	142	160	40	259	97	130	62	100
10%	111	227	110	180	80	101	202	126	91	197	109	179	95	129	142	151	95	145
12%	100	149	114	192	37	151	155	165	83	155	115	227	90	110	80	273	52	140
Replication 5																		
0%	275	308	201	265	250	304	280	315	295	245	252	252	205	225	235	240	150	390
2%	240	205	295	280	165	229	200	190	270	220	270	270	250	245	220	255	265	170
4%	235	170	275	280	140	230	195	240	210	250	210	210	335	222	195	282	240	225
6%	230	235	185	308	215	245	225	290	280	275	280	280	170	250	240	245	216	308
8%	240	220	170	300	165	154	230	145	130	355	130	130	130	225	120	135	235	150
10%	120	255	200	165	210	230	210	395	120	150	120	120	120	130	116	260	100	120
12%	165	150	125	335	50	180	150	150	250	215	250	250	85	175	155	135	150	120

Table 44. Root distribution (number of roots at 5 cm, 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	30	70	70	30	30	25	45	50	35	35	20	150	40	30	45	30	30	30
2%	70	40	8	35	20	30	25	20	60	30	10	40	30	50	3	50	38	20
4%	20	50	9	46	35	40	40	40	20	55	15	130	20	20	30	30	30	20
6%	20	70	30	12	13	65	50	100	30	20	15	26	45	40	50	20	50	90
8%	20	40	10	90	9	20	10	100	20	60	10	30	30	45	40	50	20	100
10%	30	50	20	30	40	35	15	50	10	130	18	7	20	32	60	50	30	30
12%	28	50	20	25	20	25	40	30	10	90	12	30	10	20	25	30	30	50
Replication 2																		
0%	40	80	40	50	50	80	38	45	20	60	50	40	65	50	28	36	25	28
2%	28	40	15	45	30	30	15	40	43	37	20	35	26	30	15	30	15	50
4%	18	50	20	20	25	23	15	25	20	45	15	35	20	80	20	55	20	28
6%	30	30	25	28	10	80	18	30	45	60	19	20	20	35	4	31	20	20
8%	18	28	28	25	20	100	25	20	30	40	15	20	53	30	40	28	25	30
10%	15	50	40	30	13	20	25	40	28	60	20	50	10	50	35	30	7	50
12%	13	22	15	40	14	12	19	30	8	30	20	20	22	30	15	22	30	30
Replication 3																		
0%	14	80	18	100	18	50	80	70	18	23	15	35	29	18	18	15	16	30
2%	7	100	10	17	9	25	20	15	10	30	11	20	18	20	18	13	23	16
4%	10	30	8	40	20	4	16	8	19	100	50	30	13	21	17	17	10	10
6%	13	35	18	16	12	25	6	16	10	31	10	15	10	16	15	19	14	15
8%	5	50	14	40	8	20	9	50	21	30	20	22	21	20	15	22	8	50
10%	12	20	15	14	20	20	15	30	15	30	19	30	5	20	27	21	9	30
12%	4	30	11	17	28	30	13	20	8	15	20	25	19	20	14	20	22	25

Continued →

Table 44. Root distribution (number of roots at 5 cm, 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	4	30	14	18	12	30	26	25	15	18	10	15	13	18	10	5	25	35
2%	18	12	4	16	16	28	11	20	18	31	18	30	13	30	15	23	5	8
4%	15	14	10	18	13	24	12	20	15	20	19	20	13	33	18	20	5	20
6%	28	18	10	14	24	18	18	18	8	28	10	25	9	23	14	28	10	22
8%	21	37	12	16	27	29	11	30	8	12	25	16	8	25	15	14	14	16
10%	10	30	10	18	10	21	16	30	8	48	6	30	13	30	12	35	9	16
12%	10	33	15	13	19	23	13	26	10	20	10	30	13	14	10	30	20	15
Replication 5																		
0%	40	20	29	17	18	30	20	20	25	20	25	30	14	20	25	18	15	28
2%	18	15	20	20	15	27	21	21	26	18	35	40	15	30	14	20	18	17
4%	20	27	14	15	30	18	15	15	15	27	18	18	4	38	12	30	10	16
6%	20	30	30	20	9	26	28	28	14	28	50	20	27	29	45	30	28	16
8%	23	18	20	48	15	34	15	15	23	38	15	30	13	25	10	28	47	18
10%	10	20	45	26	18	28	27	27	21	40	13	40	25	28	23	50	8	15
12%	30	30	15	60	8	21	36	36	24	23	27	27	10	20	13	18	18	17

Table 45. Aboveground biomass (weight of aboveground production (g), 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	0.3250	0.5332	0.2930	0.4563	0.3414	0.6072	0.7310	0.4087	0.4449	0.4985	0.1823	0.5976	0.2753	0.2295	0.2523	0.4270	0.2604	0.3376
2%	0.2846	0.2958	0.1960	0.3655	0.0448	0.2769	0.1948	0.3344	0.1925	0.3289	0.1184	0.6624	0.1680	0.1471	0.0269	0.3560	0.1803	0.2522
4%	0.2462	0.2604	0.0474	0.3507	0.0733	0.2736	0.1252	0.1610	0.0513	0.2380	0.1432	0.2188	0.0750	0.6180	0.0871	0.1150	0.1277	0.1208
6%	0.2143	0.3104	0.0561	0.1977	0.3300	0.2448	0.1483	0.4303	0.1281	0.2439	0.0699	0.3159	0.0703	0.2877	0.0775	0.1803	0.0647	0.1178
8%	0.0992	0.2293	0.1013	0.3218	0.0226	0.1272	0.0885	0.2990	0.0691	0.2768	0.0773	0.2727	0.0759	0.1813	0.0763	0.1671	0.0700	0.143
10%	0.5410	0.1217	0.0972	0.2881	0.0476	0.0999	0.0538	0.1551	0.0829	0.2513	0.0504	0.1090	0.0187	0.1014	0.0558	0.2006	0.0803	0.0876
12%	0.0466	0.2160	0.0590	0.2230	0.0356	0.0832	0.1080	0.1892	0.0636	0.2506	0.0487	0.2361	0.0432	0.0993	0.0605	0.1906	0.0425	0.1508
Replication 2																		
0%	0.4978	0.6383	0.4876	1.0416	0.3333	0.4224	0.388	0.6040	0.4126	1.1945	0.4832	0.8519	0.4394	1.1706	0.1522	0.4302	0.1060	0.4012
2%	0.2903	0.6881	0.1077	0.5327	0.1687	0.3623	0.094	0.3517	0.1035	0.3411	0.1725	0.4803	0.1156	0.2758	0.1605	0.2644	0.0746	0.5642
4%	0.2202	0.4080	0.2218	0.2758	0.2225	0.2629	0.1918	0.3263	0.0904	0.3918	0.0803	0.4695	0.0419	0.1279	0.0605	0.1127	0.0988	0.3292
6%	0.2341	0.2627	0.1168	0.2240	0.0235	0.2931	0.0833	0.3586	0.2153	0.2688	0.1209	0.2863	0.0567	0.1992	0.0689	0.1958	0.0693	0.2020
8%	0.1390	0.3940	0.1921	0.0753	0.0867	0.4856	0.0991	0.2731	0.1270	0.3128	0.1638	0.2508	0.0349	0.1205	0.0542	0.1458	0.0817	0.1340
10%	0.1126	0.3284	0.2080	0.4291	0.0346	0.1324	0.1127	0.1333	0.0755	0.2769	0.0926	0.3604	0.0398	0.1251	0.0642	0.1903	0.0951	0.2514
12%	0.0571	0.1831	0.1264	0.4068	0.0293	0.0780	0.0876	0.1708	0.0161	0.1503	0.0813	0.2062	0.0663	0.0904	0.0643	0.1509	0.1236	0.1183
Replication 3																		
0%	0.2825	0.4404	0.3761	0.9690	0.2909	0.3756	0.6591	0.7042	0.2096	0.8653	0.1031	0.6789	0.3337	0.2533	0.1848	0.1620	0.1823	0.4595
2%	0.2437	0.6247	0.1135	0.2313	0.6860	0.4252	0.1800	0.1987	0.0367	0.1403	0.1683	0.2859	0.0519	0.2120	0.1238	0.2553	0.1444	0.236
4%	0.5940	0.2265	0.0878	0.1982	0.1582	0.1163	0.0542	0.1542	0.0603	0.5180	0.2404	0.2809	0.0921	0.0906	0.0479	0.0866	0.0597	0.1783
6%	0.1949	0.2593	0.1347	0.0934	0.0603	0.0890	0.0445	0.1576	0.0610	0.2124	0.1876	0.1941	0.0283	0.0871	0.0558	0.0831	0.0950	0.0730
8%	0.0657	0.1831	0.0575	0.2286	0.0099	0.0696	0.0393	0.1738	0.1207	0.2865	0.1854	0.1611	0.1009	0.1488	0.0447	0.0634	0.0439	0.2032
10%	0.0898	0.1131	0.0723	0.1714	0.0290	0.1299	0.0429	0.0852	0.0647	0.1669	0.0583	0.1764	0.0073	0.1222	0.0433	0.0878	0.0503	0.2229
12%	0.0413	0.1998	0.0483	0.2944	0.0509	0.1122	0.0127	0.1581	0.0277	0.0955	0.0771	0.3633	0.0809	0.0995	0.1318	0.1114	0.0700	0.0947

Continued →

Table 45. Aboveground biomass (weight of aboveground production (g), 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	0.0011	0.4386	0.1630	0.2370	0.0990	0.6262	0.3989	0.3935	0.1270	0.1542	0.0946	0.2966	0.1014	0.2734	0.0507	0.0524	0.2357	0.5980
2%	0.1866	0.2442	0.0546	0.1267	0.3109	0.2984	0.2703	0.1195	0.0986	0.4351	0.2448	0.3153	0.1178	0.3405	0.1405	0.1939	0.1074	0.1145
4%	0.0161	0.3456	0.1569	0.3660	0.1121	0.2405	0.1337	0.4720	0.1687	0.2586	0.1221	0.4175	0.0648	0.1701	0.0680	0.2130	0.5620	0.1712
6%	0.1205	0.3199	0.0923	0.3541	0.0635	0.0521	0.0684	0.1830	0.0546	0.3029	0.0632	0.2573	0.0859	0.0223	0.0625	0.1746	0.0463	0.1310
8%	0.1494	0.1770	0.0609	0.1943	0.0242	0.0785	0.0264	0.3285	0.0312	0.1934	0.0957	0.2096	0.0129	0.1885	0.0374	0.1179	0.585	0.0576
10%	0.0498	0.2279	0.0701	0.2258	0.0321	0.0872	0.1210	0.1512	0.0292	0.1483	0.0549	0.2535	0.0307	0.0916	0.0599	0.1250	0.0310	0.0930
12%	0.0386	0.1447	0.0796	0.2714	0.0087	0.1076	0.0593	0.1659	0.0304	0.1706	0.0630	0.3290	0.0276	0.1119	0.0508	0.1779	0.0456	0.1238
Replication 5																		
0%	1.3006	0.4716	0.5529	0.7079	0.3778	0.7823	0.5258	0.5497	0.5221	0.4992	0.7353	0.5773	0.9195	0.4251	0.5577	0.3455	0.2460	0.6471
2%	0.3853	0.2093	1.0849	0.4863	0.3110	0.4053	0.2567	0.2364	0.2525	0.3024	0.9709	0.5548	0.4358	0.3943	0.4883	0.4142	0.4098	0.3872
4%	0.5923	0.2525	0.5805	0.3163	0.2128	0.2787	0.2775	0.3222	0.2108	0.3260	0.4516	0.4013	0.3481	0.2918	0.1969	0.3304	0.1543	0.2737
6%	0.3534	0.3304	0.5006	0.4166	0.0490	0.1637	0.3518	0.3580	0.2143	0.4363	0.4755	0.3056	0.1387	0.2197	0.2035	0.3478	0.3556	0.3941
8%	0.2602	0.3708	0.2295	0.5069	0.0683	0.1738	0.3552	0.2066	0.1523	0.6168	0.1076	0.4214	0.0580	0.1076	0.034	0.1062	0.3603	0.2267
10%	0.0767	0.1644	0.4332	0.1817	0.2144	0.1215	0.1724	0.2485	0.1681	0.1835	0.1287	0.5950	0.0304	0.1046	0.0414	0.3014	0.0337	0.1047
12%	0.1367	0.1773	0.0693	0.7029	0.0165	0.1159	0.1564	0.1408	0.0655	0.1164	0.1439	0.3270	0.0189	0.1567	0.1406	0.1355	0.0684	0.1252

Table 46. Belowground biomass (weight of belowground production (g), 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	0.5973	0.1514	0.3946	0.5074	0.1775	0.3879	0.3667	0.3605	0.2063	0.5354	0.1108	1.1616	0.2026	0.2569	0.1567	0.4718	0.1943	0.2609
2%	0.5054	0.1574	0.1864	0.6900	0.0236	0.6232	0.1468	0.4257	0.1590	0.7000	0.0661	0.7499	0.0864	0.4359	0.0068	0.5458	0.1545	0.3067
4%	0.3156	0.3156	0.1607	0.6601	0.1660	0.5367	0.2974	0.2888	0.1680	0.4835	0.2626	0.8099	0.1533	0.1343	0.1265	0.2723	0.0967	0.3078
6%	1.0320	0.1566	0.4308	0.1774	0.1461	0.5789	0.2934	0.7001	0.2257	0.4675	0.0980	0.5649	0.1983	0.3352	0.2789	0.2860	0.2032	0.3976
8%	0.3803	0.4005	0.1540	0.6183	0.2935	0.1623	0.1596	0.4892	0.1212	0.5494	0.1067	0.2975	0.2280	0.3028	0.1593	0.3282	0.1887	0.5839
10%	0.2558	0.2362	0.2432	0.3375	0.4016	0.3370	0.1487	0.2582	0.0924	0.6115	0.0535	0.0949	0.0885	0.3693	0.2643	0.3778	0.1265	0.2942
12%	0.4044	0.1099	0.1497	0.3835	0.0863	0.2293	0.1998	0.3753	0.1234	0.5410	0.1129	0.2999	0.1158	0.1683	0.1162	0.2245	0.0854	0.3845
Replication 2																		
0%	0.2573	0.9050	0.3646	0.6794	0.3635	0.4897	0.2875	0.4518	0.1957	0.7420	0.4278	0.5301	0.4706	0.6702	0.0679	0.2049	0.2561	0.2234
2%	0.1869	0.5476	0.0287	0.4278	0.0856	0.4110	0.0548	0.4957	0.2590	0.2949	0.1971	0.3800	0.0676	0.2907	0.2300	0.1815	0.0492	0.5586
4%	0.0695	0.4110	0.0965	0.4822	0.1198	0.3385	0.2450	0.4928	0.0980	0.3136	0.0613	0.3778	0.0599	0.1552	0.0634	0.2258	0.0844	0.3943
6%	0.2836	0.2491	0.1153	0.2041	0.0455	0.2844	0.0843	0.2688	0.2063	0.5318	0.0963	0.2978	0.10002	0.4043	0.0333	0.1877	0.1138	0.4903
8%	0.0459	0.2696	0.1147	0.0761	0.0688	0.6790	0.1410	0.3069	0.1439	0.4432	0.1363	0.2935	0.2093	0.3415	0.3718	0.1356	0.0511	0.1888
10%	0.1028	0.8801	0.1849	0.4829	0.0426	0.1795	0.1293	0.2548	0.0835	0.5780	0.0631	0.4605	0.0842	0.2778	0.1267	0.4724	0.0568	0.3838
12%	0.0873	0.2051	0.0611	0.7985	0.0583	0.0558	0.1168	0.2560	0.0338	0.4183	0.1548	0.2498	0.1442	0.2134	0.0620	0.2323	0.1245	0.2265
Replication 3																		
0%	0.0473	0.4486	0.0693	0.5324	0.0629	0.2708	0.3436	0.2824	0.0425	0.3751	0.0218	0.2350	0.0882	0.1126	0.0588	0.548	0.354	0.1708
2%	0.0970	0.7053	0.0383	0.3393	0.0185	0.2350	0.1244	0.2969	0.0130	0.2275	0.0419	0.2274	0.0344	0.1526	0.0998	0.2803	0.1231	0.1945
4%	0.0255	0.3051	0.0925	0.2225	0.0907	0.3810	0.0511	0.0891	0.0593	0.4948	0.1690	0.2319	0.0560	0.1075	0.0134	0.0810	0.0131	0.2265
6%	0.0482	0.2433	0.0378	0.0794	0.0340	0.1119	0.0337	0.2089	0.0759	0.1728	0.1411	0.1648	0.0152	0.1063	0.0642	0.0665	0.0547	0.0940
8%	0.1018	0.2485	0.0345	0.4488	0.0038	0.1168	0.0194	0.3684	0.0765	0.3165	0.1254	0.1640	0.0525	0.1872	0.0438	0.1066	0.0138	0.2256
10%	0.0425	0.1454	0.0905	0.0830	0.0586	0.2414	0.0925	0.1246	0.0281	0.2485	0.0268	0.2241	0.0101	0.2785	0.0958	0.0770	0.0407	0.2249
12%	0.0636	0.1852	0.0529	0.2737	0.0721	0.1711	0.1019	0.2902	0.0188	0.1765	0.0744	0.2465	0.0985	0.2223	0.0475	0.1157	0.0770	0.1492

Continued →

Table 46. Belowground biomass (weight of belowground production (g), 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	0.0095	0.2497	0.0296	0.2116	0.0176	0.2340	0.0865	0.1992	0.0152	0.0785	0.0090	0.1284	0.0115	0.1093	0.0099	0.0453	0.0508	0.1752
2%	0.0731	0.2679	0.0103	0.0986	0.0866	0.1069	0.1549	0.0358	0.0339	0.2659	0.0525	0.2132	0.0179	0.2465	0.0402	0.1250	0.0004	0.0491
4%	0.1260	0.2079	0.0136	0.2576	0.0281	0.3033	0.0264	0.3714	0.0822	0.2351	0.0347	0.3431	0.0385	0.2252	0.0642	0.1274	0.0175	0.1535
6%	0.0666	0.2047	0.0202	0.2550	0.0387	0.0524	0.0197	0.2335	0.0299	0.3452	0.0301	0.3269	0.0767	0.0096	0.0181	0.2156	0.0312	0.2013
8%	0.0868	0.1848	0.0464	0.1736	0.0842	0.1033	0.0396	0.4192	0.0649	0.1741	0.0263	0.1899	0.0355	0.1043	0.0189	0.1138	0.0457	0.0356
10%	0.0175	0.1846	0.0267	0.1992	0.0071	0.1165	0.0427	0.1814	0.0236	0.2914	0.0220	0.2145	0.0285	0.1391	0.0373	0.1122	0.0165	0.1423
12%	0.0177	0.1266	0.0487	0.1760	0.0202	0.1261	0.0370	0.1635	0.0073	0.1788	0.0213	0.2320	0.0245	0.1372	0.0312	0.1795	0.0197	0.1562
Replication 5																		
0%	0.2653	0.1000	0.1572	0.2050	0.0782	0.3011	0.0985	0.1481	0.1198	0.1415	0.1412	0.2593	0.0872	0.1508	0.1589	0.1244	0.0385	0.1699
2%	0.0449	0.1275	0.1129	0.4922	0.0979	0.3420	0.0371	0.2311	0.0864	0.1272	0.2635	0.4879	0.1004	0.2540	0.0873	0.1780	0.0592	0.3163
4%	0.1436	0.1982	0.0532	0.1648	0.1193	0.2975	0.0344	0.1676	0.1172	0.2199	0.1133	0.2382	0.1872	0.2924	0.0386	0.2437	0.0260	0.1002
6%	0.1141	0.4147	0.1529	0.1353	0.0122	0.1396	0.1913	0.4203	0.0477	0.4276	0.1702	0.3208	0.0484	0.1587	0.0893	0.3372	0.1032	0.1704
8%	0.0505	0.3269	0.0302	0.4440	0.0436	0.2023	0.1303	0.0896	0.0282	0.7186	0.0357	0.3172	0.0178	0.1346	0.0150	0.1373	0.1308	0.4035
10%	0.0149	0.2247	0.1326	0.1373	0.1214	0.1607	0.0964	0.2224	0.0764	0.1615	0.0668	0.7131	0.0262	0.0891	0.0464	0.2741	0.0033	0.1543
12%	0.0475	0.2322	0.0262	1.0047	0.0082	0.1529	0.1393	0.1918	0.0443	0.1371	0.0536	0.2468	0.0110	0.2308	0.0333	0.1327	0.0337	0.1370

Table 47. Measured pH (s.u., 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 1																		
0%	7.3	7.8	8.2	7.8	7.5	8.0	7.1	7.7	7.2	7.8	7.8	7.5	7.7	7.7	7.6	7.9	7.5	7.7
2%	7.9	7.8	7.9	7.6	8.2	8.3	8.1	8.2	8.4	8.1	7.9	8.1	8.2	8.2	8.2	8.1	8.0	8.2
4%	8.3	8.1	8.3	7.9	8.1	8.2	8.6	8.4	8.2	8.5	8.0	8.1	8.2	8.3	8.2	8.1	8.2	8.2
6%	8.3	8.8	8.3	8.1	8.2	8.1	8.3	8.6	8.5	8.8	8.3	8.2	8.1	8.2	8.2	8.2	8.8	8.3
8%	8.2	8.3	8.1	8.1	8.2	8.2	8.6	8.6	8.5	8.6	8.5	8.4	8.5	8.6	8.1	8.1	10.0	8.2
10%	8.0	8.2	8.0	8.1	8.0	8.0	8.7	8.6	8.6	8.7	8.4	8.6	8.3	8.1	8.0	8.5	8.0	8.1
12%	8.1	8.0	8.3	8.1	8.2	8.1	8.3	8.5	8.8	8.9	8.7	8.6	8.5	8.4	8.2	8.4	8.7	8.2
Replication 2																		
0%	7.7	7.8	7.6	7.6	7.6	7.8	7.8	7.4	7.6	7.8	7.6	7.7	7.6	7.8	7.5	7.6	7.5	7.5
2%	7.8	7.7	7.4	7.5	8.0	7.9	7.8	8.2	8.0	7.9	7.7	7.7	8.1	7.9	8.1	7.9	7.8	7.9
4%	7.8	8.1	8.1	8.0	8.0	7.9	8.1	8.3	8.0	8.1	8.2	7.9	8.2	8.2	7.8	7.8	7.8	8.0
6%	8.1	8.2	8.0	7.8	8.0	8.4	8.6	8.3	8.4	8.5	8.3	8.2	8.2	8.1	7.3	8.3	8.3	7.9
8%	8.1	8.1	8.2	8.6	8.1	8.0	8.7	8.4	8.5	8.4	8.4	8.3	8.4	8.2	8.1	8.0	8.2	7.9
10%	8.3	8.0	8.0	8.3	8.0	8.2	8.5	8.7	8.5	8.5	8.4	8.2	8.1	8.3	8.1	8.1	8.1	8.2
12%	8.2	8.0	8.0	8.0	8.1	8.2	8.5	8.6	8.6	8.2	8.4	8.4	8.3	8.2	8.2	8.1	8.9	8.2
Replication 3																		
0%	7.6	8.0	7.9	7.8	7.5	7.7	7.9	7.6	7.7	7.5	7.7	7.7	7.3	7.7	7.6	7.8	7.6	7.5
2%	7.7	7.9	7.7	7.7	8.0	8.1	8.2	8.5	8.1	8.3	7.7	7.8	8.0	8.0	7.9	8.2	7.8	8.1
4%	8.0	8.2	8.6	8.2	8.1	8.2	8.1	8.4	8.1	8.4	8.2	8.2	7.9	8.3	8.0	8.0	8.1	8.1
6%	8.0	8.0	7.8	7.9	7.9	8.1	8.5	8.3	8.6	8.1	8.4	8.3	8.2	8.1	8.0	8.0	8.1	8.0
8%	8.3	8.2	8.2	8.3	7.8	8.3	8.3	8.6	8.5	8.5	8.6	8.5	8.4	8.1	8.1	8.5	7.9	8.2
10%	8.3	8.3	8.0	8.3	7.9	8.2	8.5	8.6	8.5	8.5	8.6	8.7	8.2	8.3	8.1	8.2	7.8	8.2
12%	8.2	8.3	8.0	8.0	8.0	8.3	8.3	8.7	8.6	8.6	8.7	8.5	8.5	8.5	8.3	8.1	8.2	7.9

Continued →

Table 47. Measured pH (s.u., 90 day growth) in Plant Growth Center soil amended with alkaline industrial by-products and commercial grade lime – Continued.

	Greymont LKD		Tacoma LKD		MT Limestone LKD		Holnam (CH_4) CKD		Holnam (Coal, Coke) CKD		Ash Grove CKD		Dicalcium Silicate		Carbide Lime		$CaCO_3$/CaO	
	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW	RT	BW
Replication 4																		
0%	7.5	7.6	7.3	7.4	7.6	7.5	7.3	8.0	7.4	7.0	8.5	7.5	7.9	8.5	7.4	8.5	7.4	7.3
2%	7.7	7.8	7.6	7.4	8.1	8.0	7.7	7.7	7.9	7.8	8.0	7.8	8.2	7.6	7.8	7.7	7.6	7.9
4%	7.9	8.6	7.9	7.7	7.9	8.0	8.4	8.2	8.1	8.2	7.9	8.1	8.6	7.8	7.5	7.7	7.8	7.9
6%	8.0	8.0	8.0	7.9	7.7	7.9	8.3	8.3	8.3	8.3	8.1	8.0	8.1	8.0	7.3	7.6	7.9	7.8
8%	7.8	7.9	7.9	8.0	7.9	8.0	8.3	8.3	8.2	8.3	8.2	8.4	8.0	7.9	7.8	7.8	7.8	8.6
10%	7.8	7.9	8.0	7.9	7.8	7.9	8.4	8.5	8.3	8.3	8.4	8.3	8.2	8.3	7.9	7.6	8.0	8.3
12%	7.9	7.9	7.7	8.0	7.8	7.9	8.4	8.4	8.5	8.3	8.4	7.7	8.1	8.2	7.8	8.2	8.1	7.9
Replication 5																		
0%	7.6	7.4	7.8	7.7	8.3	7.6	7.6	7.8	7.7	7.7	7.5	7.6	7.9	7.7	7.7	7.7	7.7	7.9
2%	7.9	7.9	7.6	7.8	8.1	8.1	7.8	8.0	7.9	8.2	7.7	7.8	8.3	7.9	8.0	7.9	7.7	8.0
4%	8.1	7.9	8.1	7.9	8.0	8.2	8.4	8.2	8.2	8.2	8.1	8.2	8.1	7.9	8.2	7.9	8.0	8.2
6%	7.8	7.6	7.9	8.3	8.0	7.9	8.5	8.4	8.7	8.3	8.2	8.1	8.2	8.1	8.2	8.1	7.8	8.2
8%	8.0	8.1	8.1	8.0	7.8	8.0	8.3	8.3	8.5	8.4	8.6	8.3	8.0	7.9	8.1	7.9	8.1	8.1
10%	8.0	7.7	7.8	8.1	8.3	7.9	8.5	8.6	8.5	7.2	8.8	8.4	8.6	7.9	8.5	7.9	8.9	8.5
12%	7.9	7.9	9.0	8.1	7.9	8.2	8.4	8.3	8.6	8.3	8.4	8.5	8.1	8.3	7.9	8.3	7.9	7.9